Understanding Java Garbage Collection

A Shallow Dive into the Deep End of the JVM

A presentation to the Philadelphia JUG
April 14, 2014

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This Talk’s Purpose / Goals

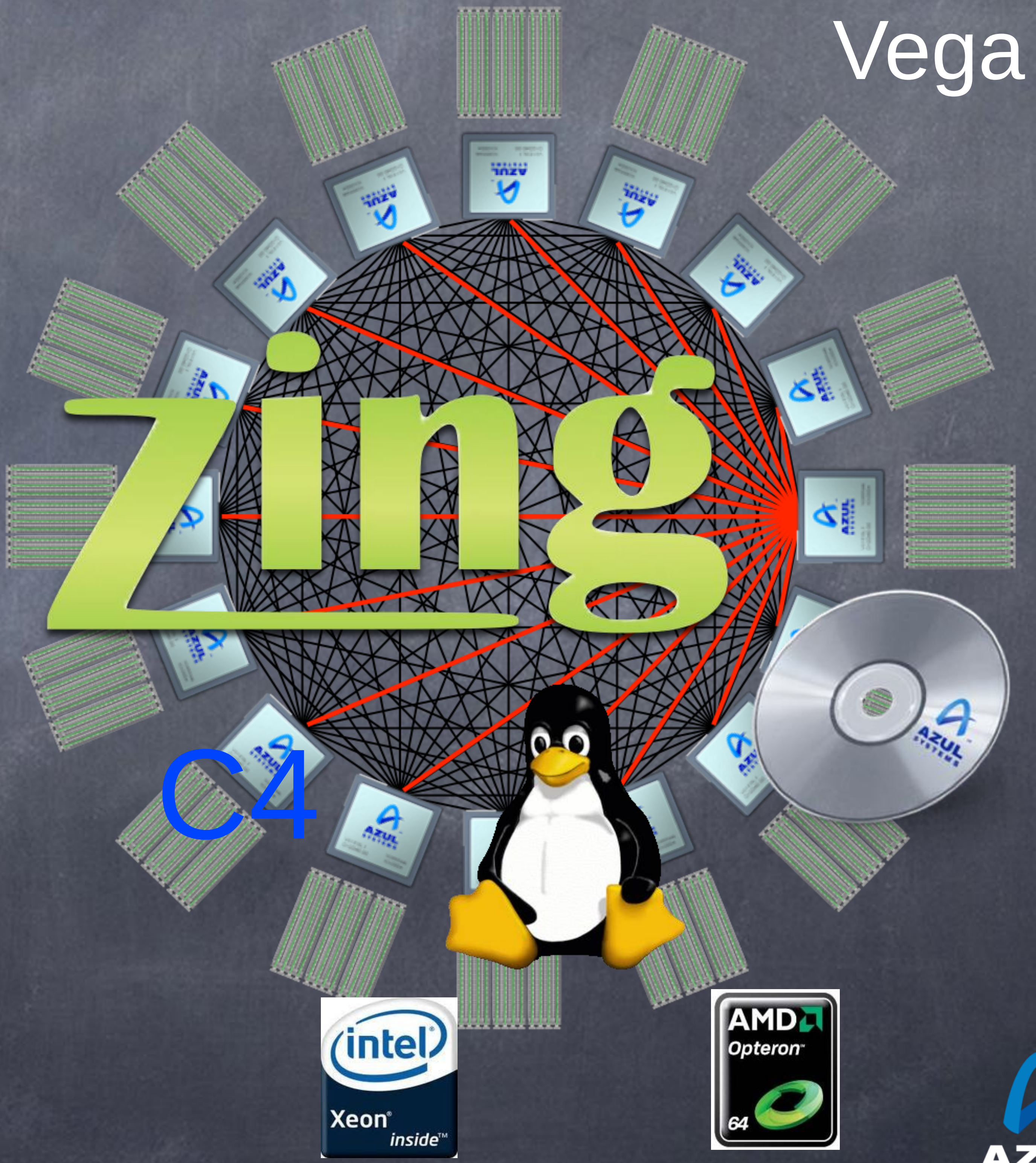
- As billed, this talk begins with OOMEs.
- But really this talk is focused on GC education
- This is a talk about how the “GC machine” works
- Purpose: Once you understand how it works, you can use your own brain...
- You’ll learn just enough to be dangerous...
- The “Azul makes the world’s greatest GC” stuff will only come at the end, I promise...

About Azul Systems

- We deal with Java performance issues on a daily basis
  - Our solutions focus on consistent response time under load
  - We enable practical, full use of hardware resources
- As a result, we often help characterize problems
- In many/most cases, it’s not the database, app, or network - it’s the JVM, or the system under it…
  - GC Pauses, OS or Virtualization “hiccups”, swapping, etc.
- We use and provide simple tools to help discover what’s going on in a JVM and the underlying platform
  - Focus on measuring JVM/Platform behavior with your app
  - Non-intrusive, no code changes, easy to add

About Azul

- We make scalable Virtual Machines
- Have built “whatever it takes to get job done” since 2002
- 3 generations of custom SMP Multi-core HW (Vega)
- Now Pure software for commodity x86 (Zing)
- “Industry firsts” in Garbage collection, elastic memory, Java virtualization, memory scale



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High level agenda

- What is an OOME and why does it hurt so good?
- GC fundamentals and key mechanisms
- Some GC terminology & metrics
- Classifying current commercially available collectors
- Why Stop-The-World is a problem
- The C4 collector: What a solution to STW looks like...

March PhillyJUG: Claim 1

- Java is Slow!
- Until Hotspot kicks in, JVM is an interpreter
    - ○ And even Hotspot can’t match hand-tuned libraries
- Startup loads lots of classes
    - ○ Don’t use Spring for a command-line filter app
- GC can create inconvenient pauses

--Keith Gregory

http://www.kdgregory.com/misc/presentations/kdgregory-com-presentation-JVM_Internals.pdf

March PhillyJUG: Claim 2

- Java Uses Too Much Memory!
- Don’t confuse virtual and resident memory
  - JVM will reserve max heap from OS
  - OS will assign physical memory as needed
- Memory is under $15/Gb
- But that isn’t a license to go wild
  - Large heaps == lots of garbage when collector runs
  - Over-committing can lead to big problems

--Keith Gregory

http://www.kdgregory.com/misc/presentations/kdgregory-com-presentation-JVM_Internals.pdf

OOMEs: the Usual Suspects

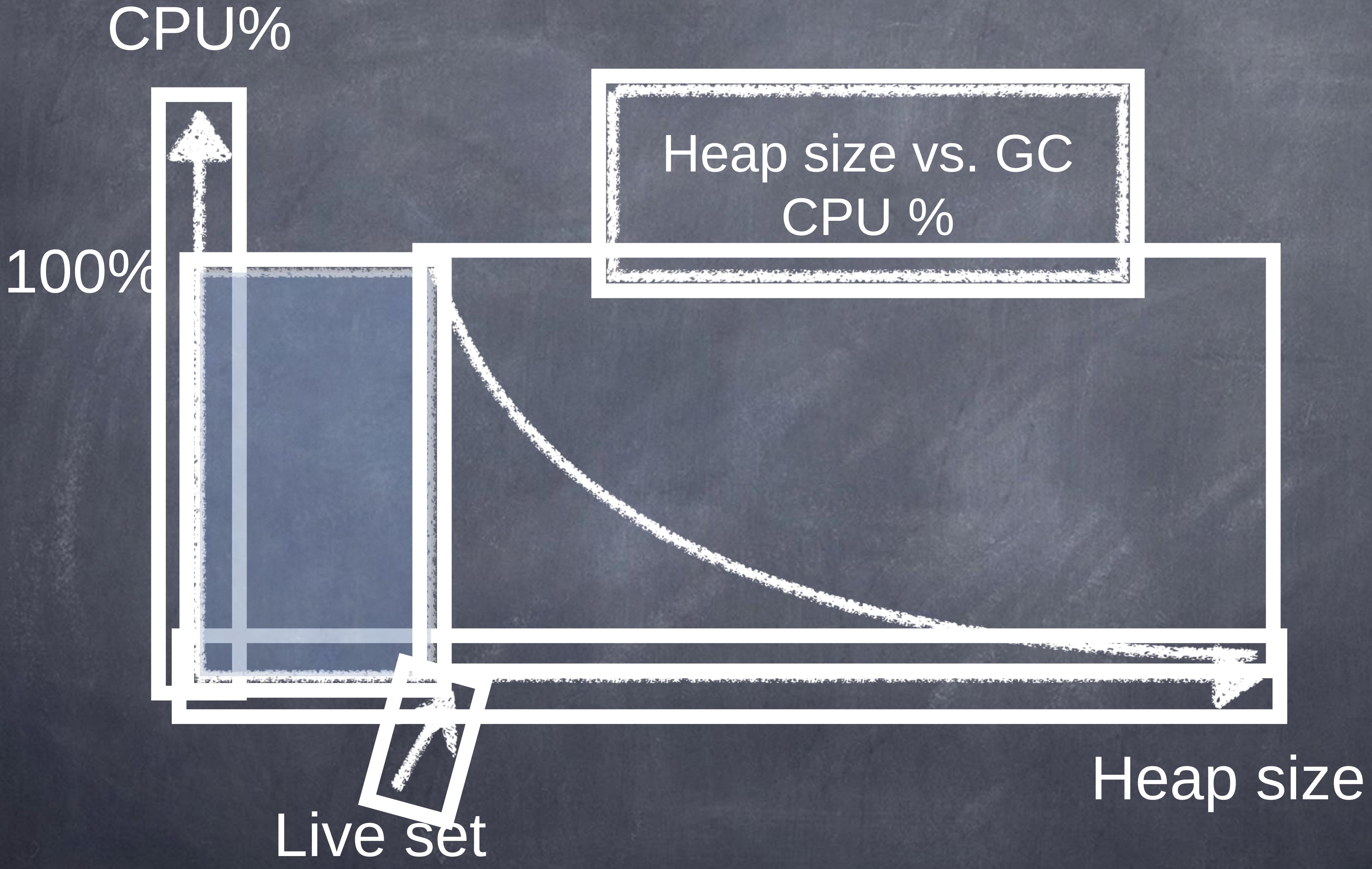
- There actually four categories of memory issues with similar and overlapping symptoms, but varied causes and solutions:
- **Performance**: usually associated with excessive object creation and deletion, long delays in garbage collection, excessive operating system page swapping, and more.
- **Resource constraints:** occurs when there's either to little memory available or your memory is too fragmented to allocate a large object—this can be native or, more commonly, Java heap-related.
- **Java heap leaks:** the classic memory leak, in which Java objects are continuously created without being released. This is usually caused by latent object references.
- **Native memory leaks:** associated with any continuously growing memory utilization that is outside the Java heap, such as allocations made by JNI code, drivers or even JVM allocations.

Out of Memory Exception

- **Why didn’t my app throw an OutOfMemoryError?**
- Posted by kcpeppe on January 8, 2014 at 8:19 AM PST
- Every once in a while I run into someone that has a JVM that is running back to back collections and yet the heap is still almost full after each attempt! When they discover that their problem is related to the JVM not having enough memory they often ask the question, why didn't the JVM throw an OutOfMemoryError? After all my application is not making any forward progress and the reason is Java heap is almost completely exhausted.

Empty memory and CPU/throughput

Heap size vs. GC CPU %



Two Intuitive limits

- If we had exactly 1 byte of empty memory at all times, the collector would have to work “very hard”, and GC would take 100% of the CPU time
- If we had infinite empty memory, we would never have to collect, and GC would take 0% of the CPU time
- GC CPU % will follow a rough 1/x curve between these two limit points, dropping as the amount of memory increases.

Empty memory needs

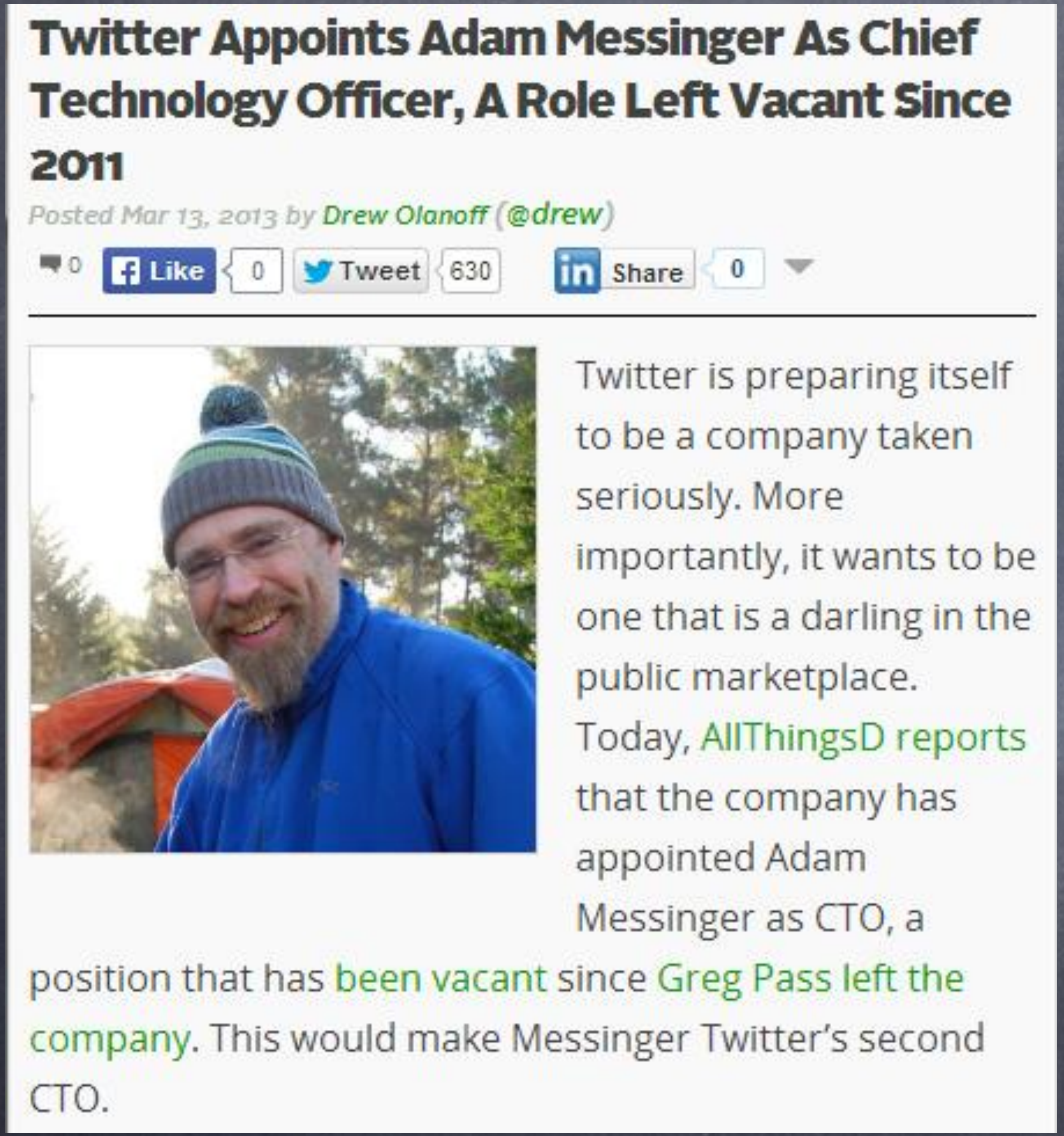
(empty memory == CPU power)

- The amount of empty memory in the heap is the dominant factor controlling the amount of GC work
- The amount of memory recovered per cycle is equal to the amount of unused memory (heap size - live set)
- The collector has to perform a GC cycle when the empty memory runs out
- The efficiency of collectors that pause for sweeping doubles with every doubling of the empty memory

What empty memory controls

- Empty memory controls efficiency (amount of collector work needed per amount of application work performed)
- Empty memory controls the frequency of pauses (if the collector performs any Stop-the-world operations)
- Empty memory DOES NOT control pause times (only their frequency)
- In collectors that pause for sweeping, more empty memory means less frequent but LARGER pauses

Is GC still a real problem?



Twitter Appoints Adam Messinger As Chief Technology Officer, A Role Left Vacant Since 2011

Posted Mar 13, 2013 by Drew Olanoff (@drew)

Twitter is preparing itself to be a company taken seriously. More importantly, it wants to be one that is a darling in the public marketplace. Today, AllThingsD reports that the company has appointed Adam Messinger as CTO, a position that has been vacant since Greg Pass left the company. This would make Messinger Twitter's second CTO.

"The one big challenge left for Java on performance is containing pause times. Latency jitter is the only reason to ever use other languages inside Twitter."

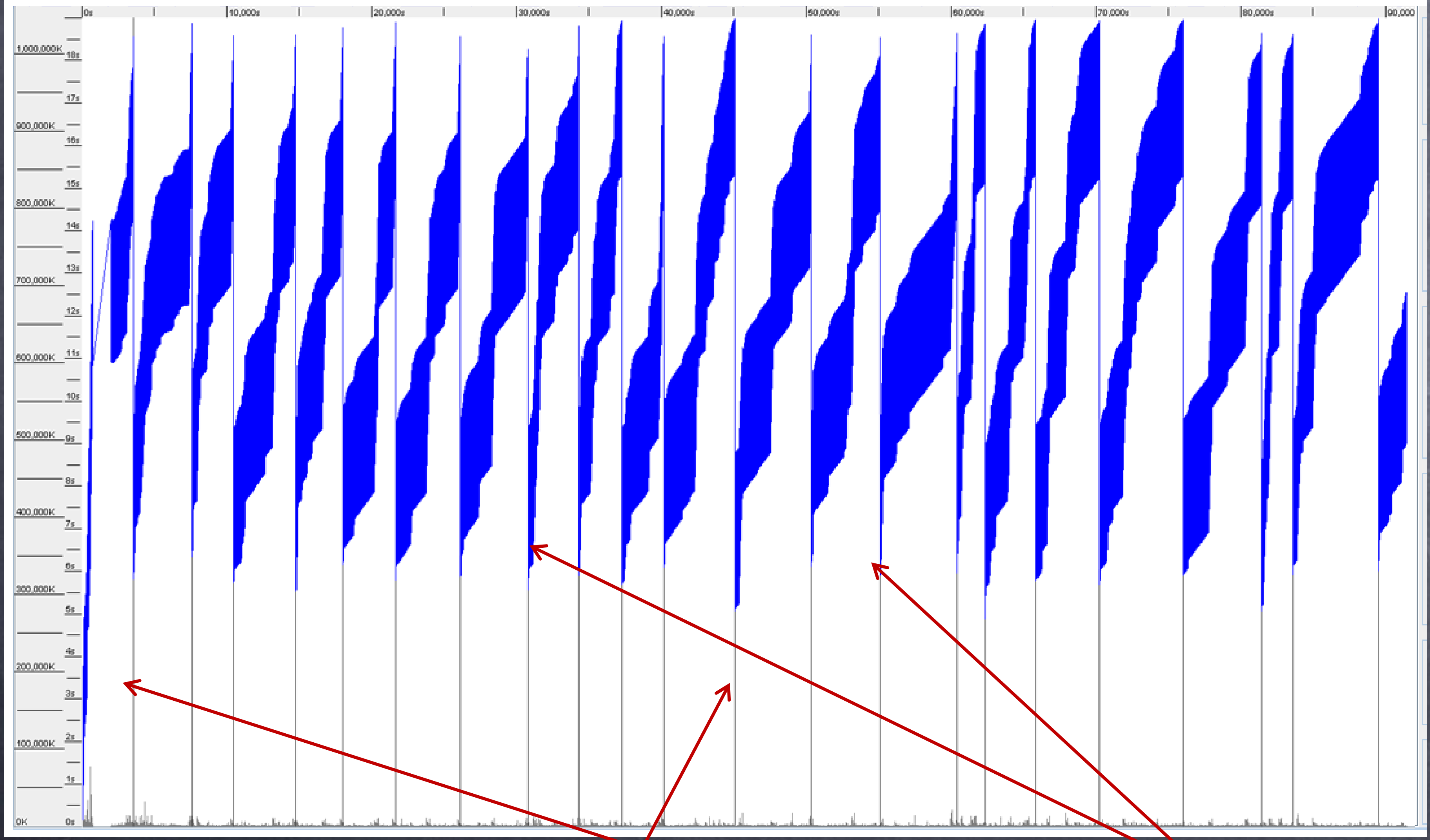
--Adam Messinger, CTO of Twitter

Citation: ***Oracle Java 8 global launch video, March 25, 2014***

GC behavior of a JVM with little heap tuning

-Xms1024m -Xmx1024m -XX:NewSize=200m -XX:MaxNewSize=200m

Heap used over a period of about 25 hours:



Many Old Generation Full GC (the grey lines)

Blue = Heap occupancy

New generation GC pauses on average occurred **every 6 seconds** and lasted **less than 50 milliseconds**.

Any single pause is unnoticeable to the users waiting for the server's response.

Old generation pauses on average occurred **less than once per hour** but lasted as much as almost **8 seconds** on average with a single outlier even reaching **19 seconds.**

Memory use

- How many of you use heap sizes of:
- ☞ more than ½ GB?
- ☞ more than 1 GB?
- ☞ more than 2 GB?
- ☞ more than 4 GB?
- ☞ more than 10 GB?
- ☞ more than 20 GB?
- ☞ more than 50 GB?
- ☞ more than 100 GB?

Why should you understand (at least a little) how GC works?

Much of what People seem to “know” about Garbage Collection is wrong

- In many cases, it’s much better than you may think
  - GC is extremely efficient. Much more so that malloc()
  - Dead objects cost nothing to collect
  - GC will find <u>all</u> the dead objects (including cyclic graphs)
  - ...
- In many cases, it’s much worse than you may think
  - Yes, it really does stop for ~1 sec per live GB
  - No, GC does not mean you can’t have memory leaks
  - No, those pauses you eliminated from your 20 minute test are not gone
  - ...

Trying to solve GC problems in application architecture is like throwing knives

- You probably shouldn’t do it blindfolded
- It takes practice to do it well without hurting people
- You can get very good at it, but do you really want to?
  - Will all the code you leverage be as good as yours?
- Examples of “GC friendly” techniques:
  - Object pooling
  - Off heap storage
  - Distributed heaps
  - ...
  - (In most cases, you end up building your own garbage collector)

Some GC Terminology

Classifying a collector’s operation

- A Concurrent Collector performs garbage collection work concurrently with the application’s own execution
- A Parallel Collector uses multiple CPUs to perform garbage collection
- A Stop-the-World collector performs garbage collection while the application is completely stopped
- An Incremental collector performs a garbage collection operation or phase as a series of smaller discrete operations with (potentially long) gaps in between
- Mostly means sometimes it isn’t (usually means a different fall back mechanism exists)

Compact

- Over time, heap will get “swiss cheesed”: contiguous dead space between objects may not be large enough to fit new objects (aka “fragmentation”)
- Compaction moves live objects together to reclaim contiguous empty space (aka “relocate”)
- Compaction has to correct all object references to point to new object locations (aka “remap”)
- Remap scan must cover all references that could possibly point to relocated objects
- Note: work is generally linear to “live set”

Copy

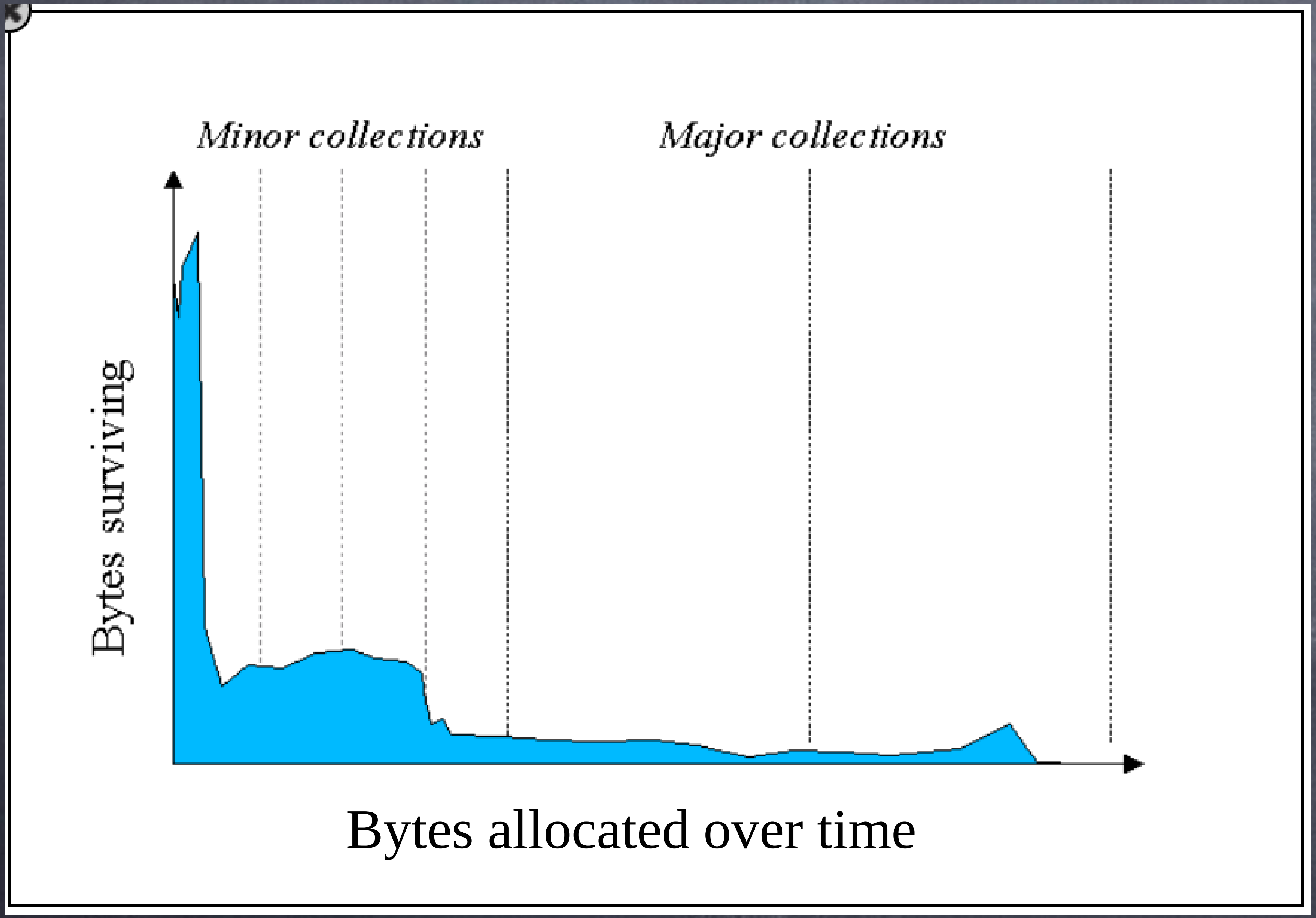
- A copying collector moves all lives objects from a “from” space to a “to” space & reclaims “from” space
- At start of copy, all objects are in “from” space and all references point to “from” space.
- Start from “root” references, copy any reachable object to “to” space, correcting references as we go
- At end of copy, all objects are in “to” space, and all references point to “to” space
- Note: work generally linear to “live set”

Generational Collection

- Weak Generational Hypothesis; “most objects die young”
- Focus collection efforts on young generation:
  - Use a moving collector: work is linear to the live set
  - The live set in the young generation is a small % of the space
  - Promote objects that live long enough to older generations
- Only collect older generations as they fill up
  - “Generational filter” reduces rate of allocation into older generations
- Tends to be (order of magnitude) more efficient
  - Great way to keep up with high allocation rate
  - Practical necessity for keeping up with processor throughput

Why Generational Garbage Collection

Here is an example of such data. Y axis = number of bytes allocated; X access = number of bytes allocated over time



Having to mark and compact all the objects in a JVM is inefficient. As more and more objects are allocated, the list of objects grows and grows leading to longer and longer garbage collection time.

However, empirical analysis of applications has shown that most objects are short lived. This is called the 'weak generational hypothesis'

As you can see, fewer and fewer objects remain allocated over time. In fact most objects have a very short life as shown by the higher values on the left side of the graph

X = number of Bytes allocated; Y = number of Bytes allocated over time

Useful terms for discussing garbage collection

- Mutator
  - Your program…
- Parallel
  - Can use multiple CPUs
- Concurrent
  - Runs concurrently with program
- Pause
  - A time duration in which the mutator is not running any code
- Stop-The-World (STW)
  - Something that is done in a pause
- Monolithic Stop-The-World
  - Something that must be done in it’s entirety in a single pause

- Generational
  - Collects young objects and long lived objects separately.
- Promotion
  - Allocation into old generation
- Marking
  - Finding all live objects
- Sweeping
  - Locating the dead objects
- Compaction
  - Defragments heapMoves objects in memory. Remaps all affected references. Frees contiguous memory regions

Useful metrics for discussing garbage collection

- Heap population (aka Live set)
  - How much of your heap is alive
- Allocation rate
  - How fast you allocate
- Mutation rate
  - How fast your program updates references in memory
- Heap Shape
  - The shape of the live object graph
  - * Hard to quantify as a metric...
- Object Lifetime
  - How long objects live

- Cycle time
  - How long it takes the collector to free up memory
- Marking time
  - How long it takes the collector to find all live objects
- Sweep time
  - How long it takes to locate dead objects
  - * Relevant for Mark-Sweep
- Compaction time
  - How long it takes to free up memory by relocating objects
  - * Relevant for Mark-Compact

Classifying common collectors

HotSpot™ ParallelGC
Collector mechanism classification

- Monolithic Stop-the-world copying NewGen
- Monolithic Stop-the-world Mark/Sweep/Compact OldGen

HotSpot™ ConcMarkSweepGC (aka CMS)

Collector mechanism classification

- Monolithic Stop-the-world copying NewGen (ParNew)
- Mostly Concurrent, non-compacting OldGen (CMS)
    - Mostly Concurrent marking
        - Mark concurrently while mutator is running
        - Track mutations in card marks
        - Revisit mutated cards (repeat as needed)
        - Stop-the-world to catch up on mutations, ref processing, etc.
    - Concurrent Sweeping
    - Does not Compact (maintains free list, does not move objects)
- Fallback to Full Collection (Monolithic Stop the world).
    - Used for Compaction, etc.

HotSpot™ G1GC (aka “Garbage First”)

Collector mechanism classification

- Monolithic Stop-the-world copying NewGen
- Mostly Concurrent, OldGen marker
    - Mostly Concurrent marking
        - Stop-the-world to catch up on mutations, ref processing, etc.
    - Tracks inter-region relationships in remembered sets
- Stop-the-world mostly incremental compacting old gen
    - Objective: “Avoid, as much as possible, having a Full GC…”
    - Compact sets of regions that can be scanned in limited time
    - Delay compaction of popular objects, popular regions
- Fallback to Full Collection (Monolithic Stop the world).
    - Used for compacting popular objects, popular regions, etc.

Delaying the inevitable

- Some form of copying/compaction is inevitable in practice
  - And compacting anything requires scanning/fixing all references to it
- Delay tactics focus on getting “easy empty space” first
  - This is the focus for the vast majority of GC tuning
- Most objects die young [Generational]
  - So collect young objects only, as much as possible. Hope for short STW.
  - **But eventually, some old dead objects must be reclaimed**
- Most old dead space can be reclaimed without moving it
  - [e.g. CMS] track dead space in lists, and reuse it in place
  - But eventually, space gets fragmented, and needs to be moved
- Much of the heap is not “popular” [e.g. G1, “Balanced”]
  - A non popular region will only be pointed to from a small % of the heap
  - So compact non-popular regions in short stop-the-world pauses
  - But eventually, popular objects and regions need to be compacted
  - Young generation pauses are only small because heaps are tiny
  - A 200GB heap will regularly have several GB of live young stuff…

Monolithic-STW GC Problems

One way to deal with Monolithic-STW GC

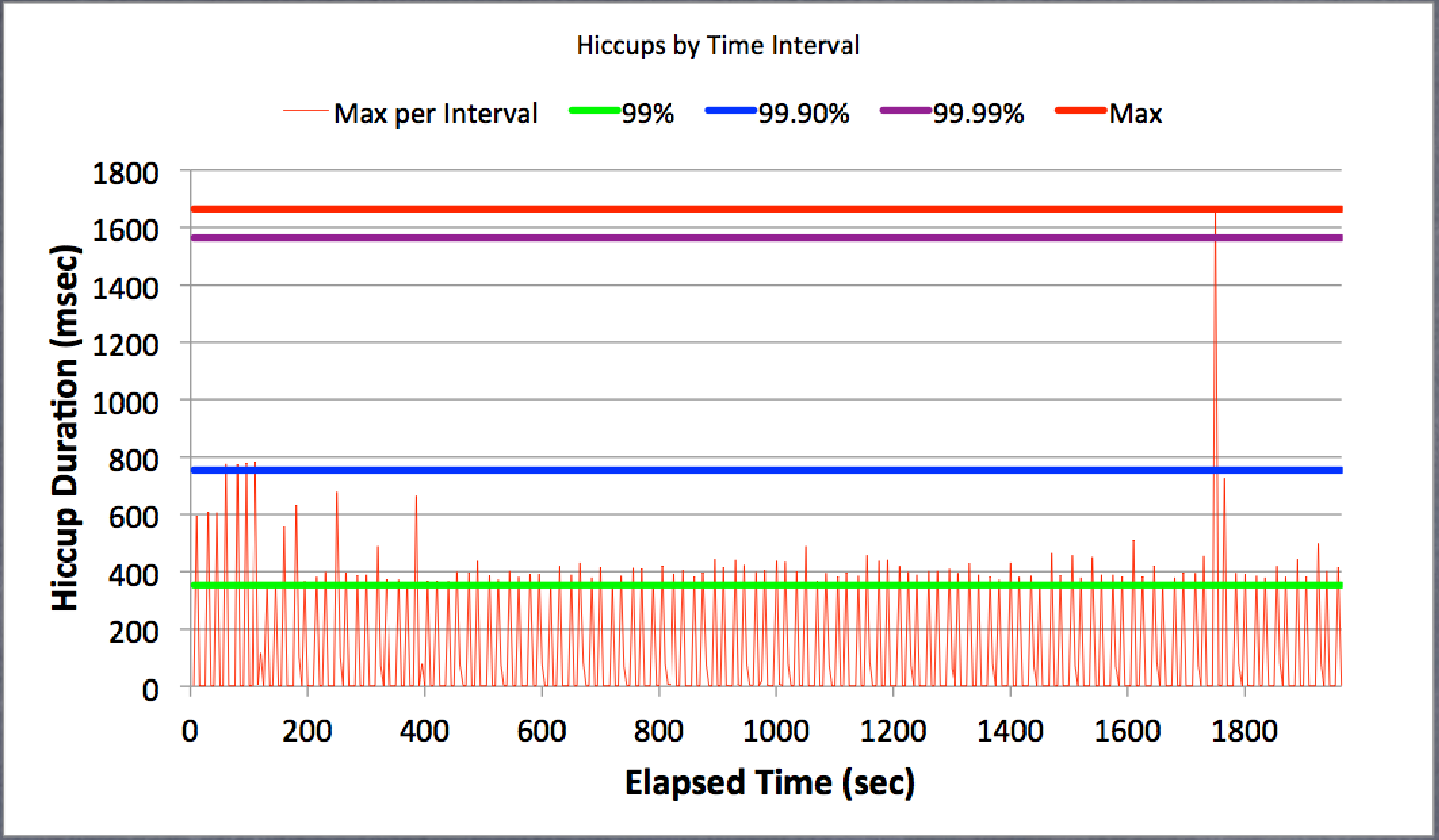
Another way to cope: “Creative Language”

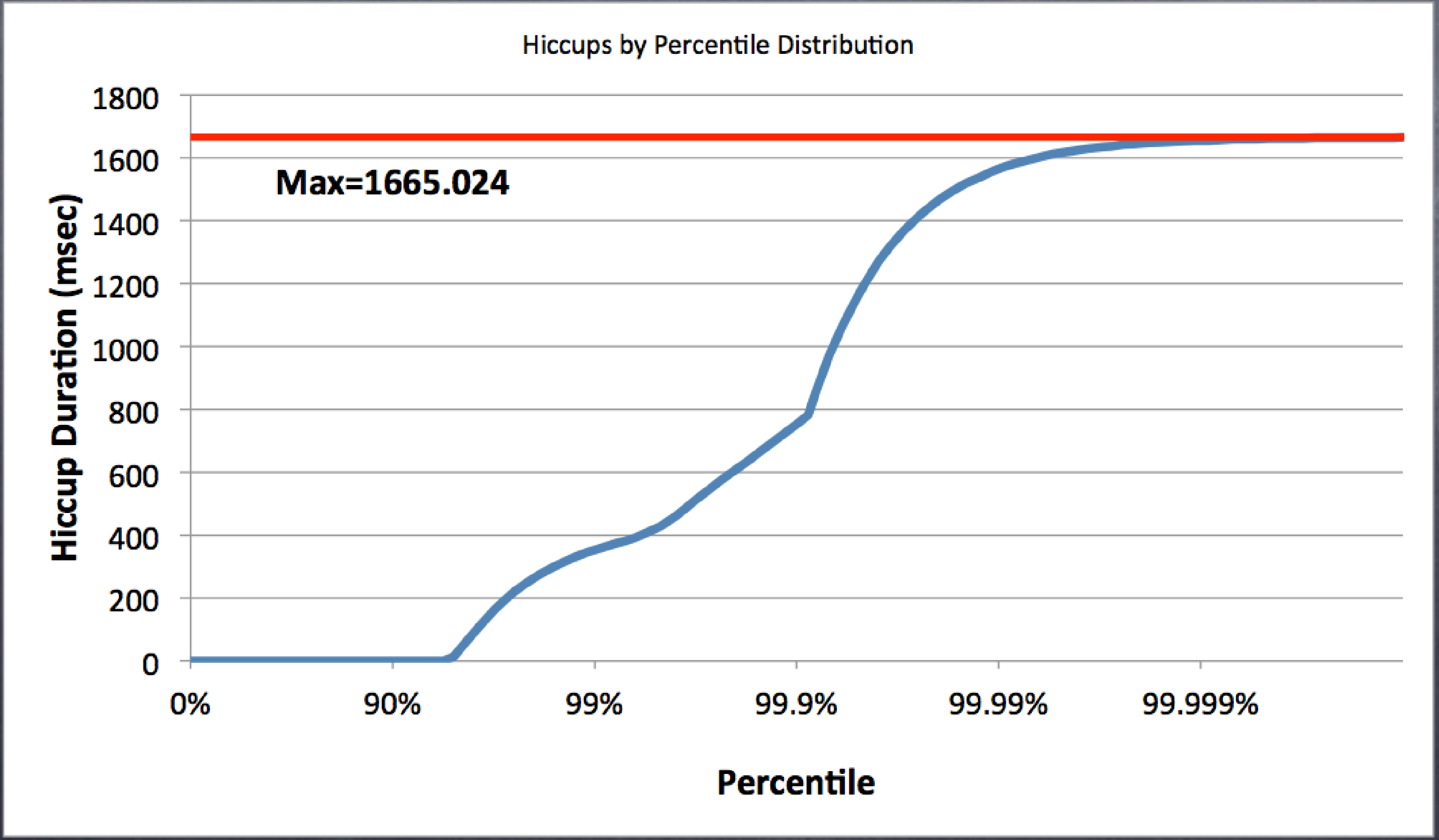
- “Guarantee a worst case of X msec, 99% of the time”
- “Mostly” Concurrent, “Mostly” Incremental
  - Translation: “Will at times exhibit long monolithic stop-the-world pauses”
- “Fairly Consistent”
  - Translation: “Will sometimes show results well outside this range”
- “Typical pauses in the tens of milliseconds”
  - Translation: “Some pauses are much longer than tens of milliseconds”

Actually measuring things

(e.g. jHiccup)

Incontinuities in Java platform execution





Getting past a monolithic-STW Garbage Collection world

We need to solve the right problems

- Scale is artificially limited by responsiveness
- Responsiveness must be unlinked from scale:
  - Heap size, Live Set size, Allocation rate, Mutation rate
  - Transaction Rate, Concurrent users, Data set size, etc.
  - Responsiveness must be continually sustainable
  - Can’t ignore “rare” events
- Eliminate all Stop-The-World Fallbacks
  - At modern server scales, any STW fall back is a failure

The problems that need solving

(areas where the state of the art needs improvement)

- Robust Concurrent Marking
  - In the presence of high mutation and allocation rates
  - Cover modern runtime semantics (e.g. weak refs, lock deflation)
- Compaction that is not monolithic-stop-the-world
  - E.g. stay responsive while compacting ¼ TB heaps
  - Must be robust: not just a tactic to delay STW compaction
  - [current “incremental STW” attempts fall short on robustness]
- Young-Gen that is not monolithic-stop-the-world
  - Stay responsive while promoting multi-GB data spikes
  - Concurrent or “incremental STW” may both be ok
  - Surprisingly little work done in this specific area

Azul's "C4" Collector

Continuously Concurrent Compacting Collector

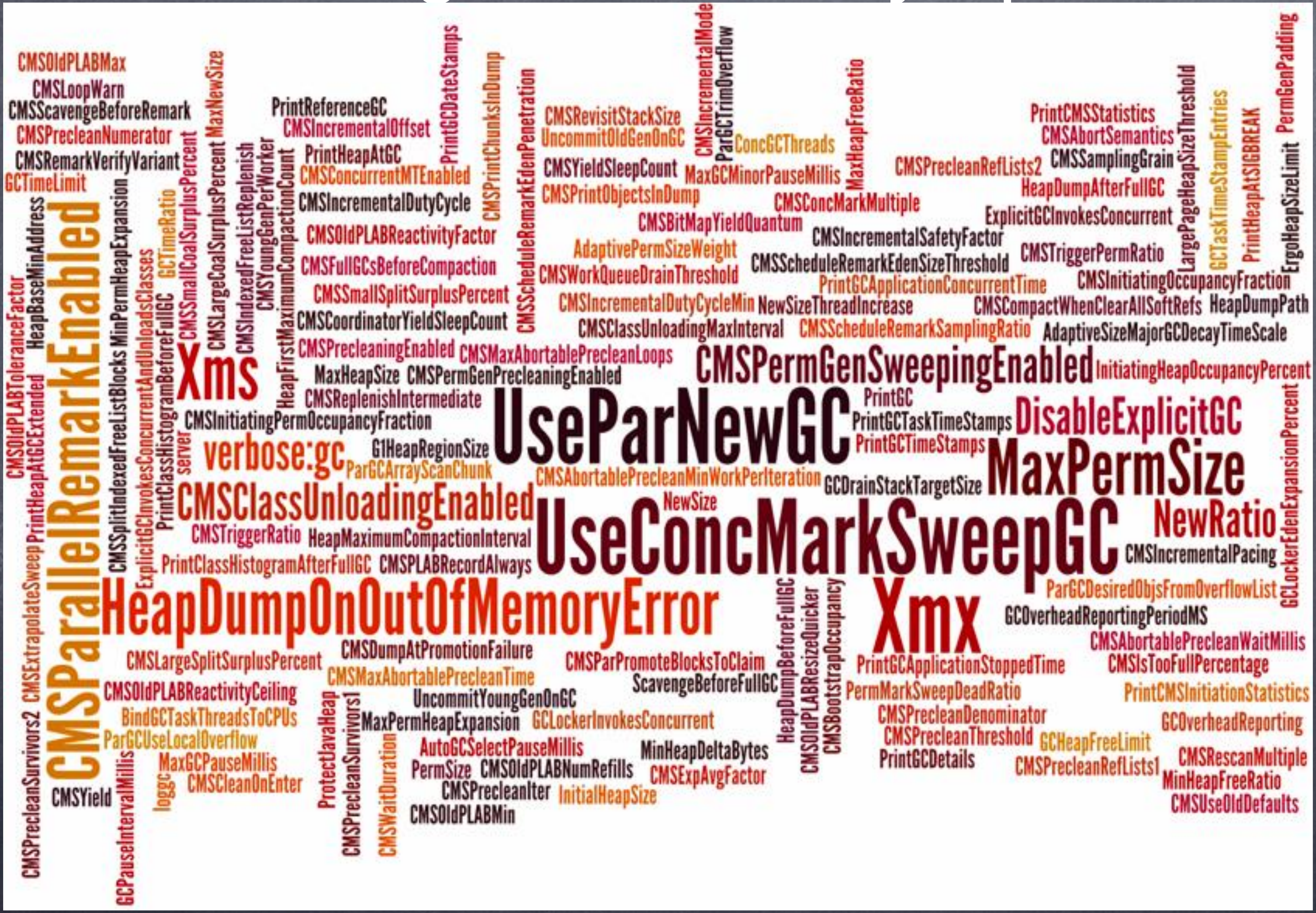
- Concurrent guaranteed-single-pass marker
  - Oblivious to mutation rate
  - Concurrent ref (weak, soft, final) processing
- Concurrent Compactor
  - Objects moved without stopping mutator
  - References remapped without stopping mutator
  - Can relocate entire generation (New, Old) in every GC cycle
- Concurrent, compacting old generation
- Concurrent, compacting new generation
- No stop-the-world fallback
  - Always compacts, and always does so concurrently

C4 algorithm highlights

- Same core mechanism used for both generations
  - Concurrent Mark-Compact
- A Loaded Value Barrier (LVB) is central to the algorithm
  - Every heap reference is verified as “sane” when loaded
  - “Non-sane” refs are caught and fixed in a self-healing barrier
- Refs that have not yet been “marked through” are caught
  - Guaranteed single pass concurrent marker
- Refs that point to relocated objects are caught
  - Lazily (and concurrently) remap refs, no hurry
  - Relocation and remapping are both concurrent
- Uses “quick release” to recycle memory
  - Forwarding information is kept outside of object pages
  - Physical memory released immediately upon relocation
  - “Hand-over-hand” compaction without requiring empty memory

GC Tuning

GC Tuning – how many options?



Copyright Frank Pavageau

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 …
```

The complete guide to Zing GC tuning

- java -Xmx40g

Fun with jHiccup

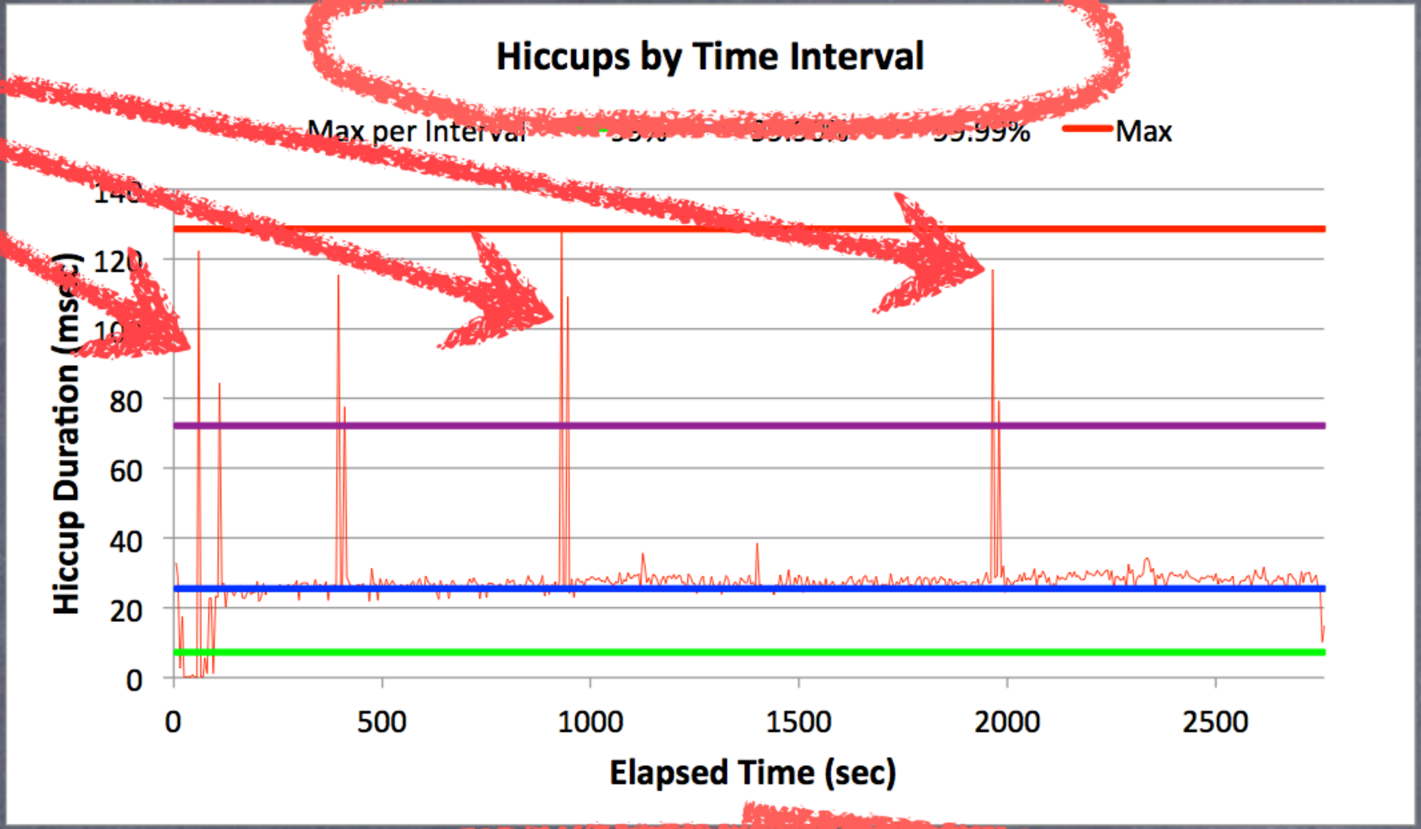
Charles Nutter @headius 20 Jan

jHiccup, @AzulSystems' free tool to show you why your JVM sucks compared to Zing: bit.ly/wsH5A8 (thx @bascule)

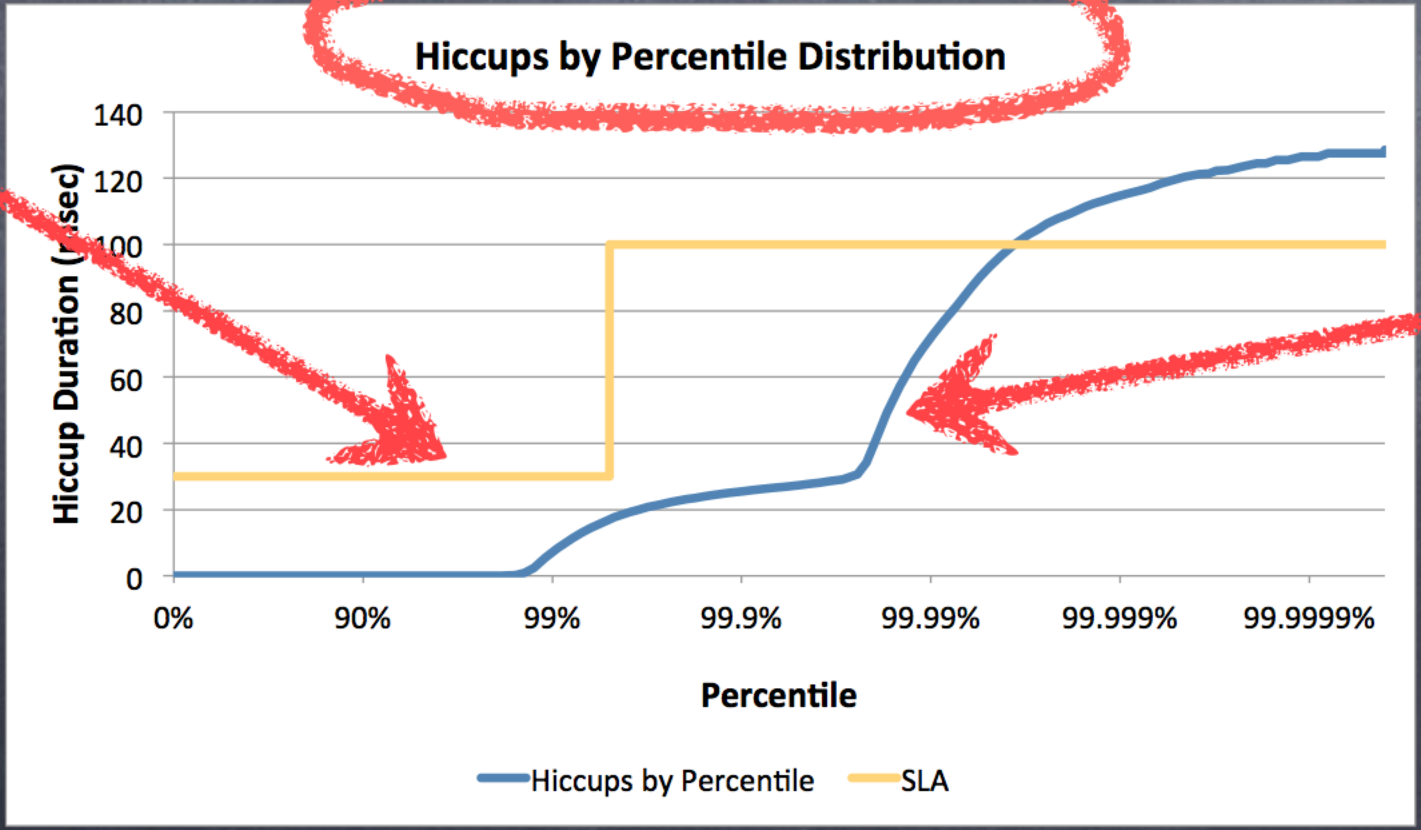
Retweeted by Gil Tene

Telco App Example

Max Time per interval

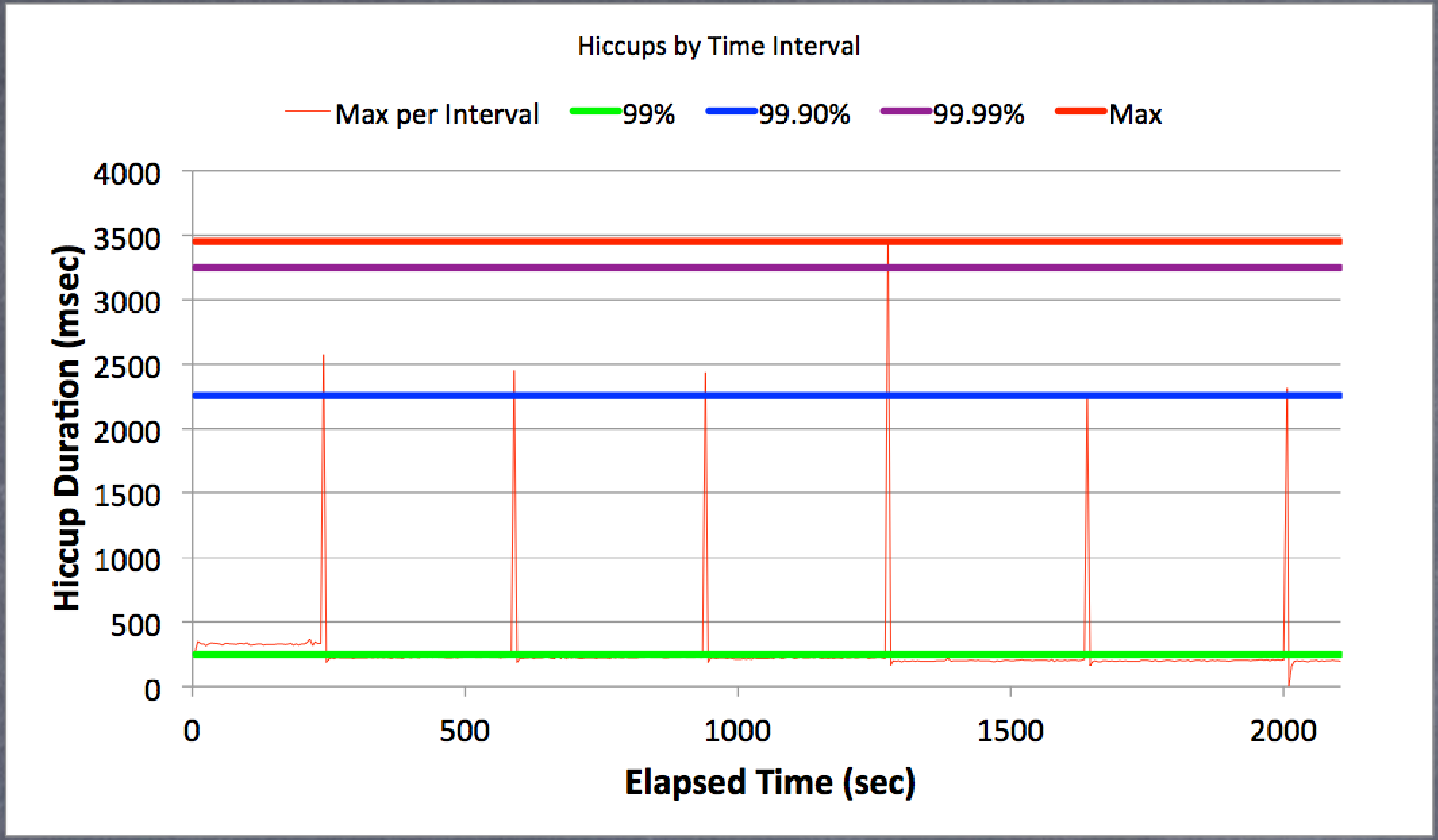


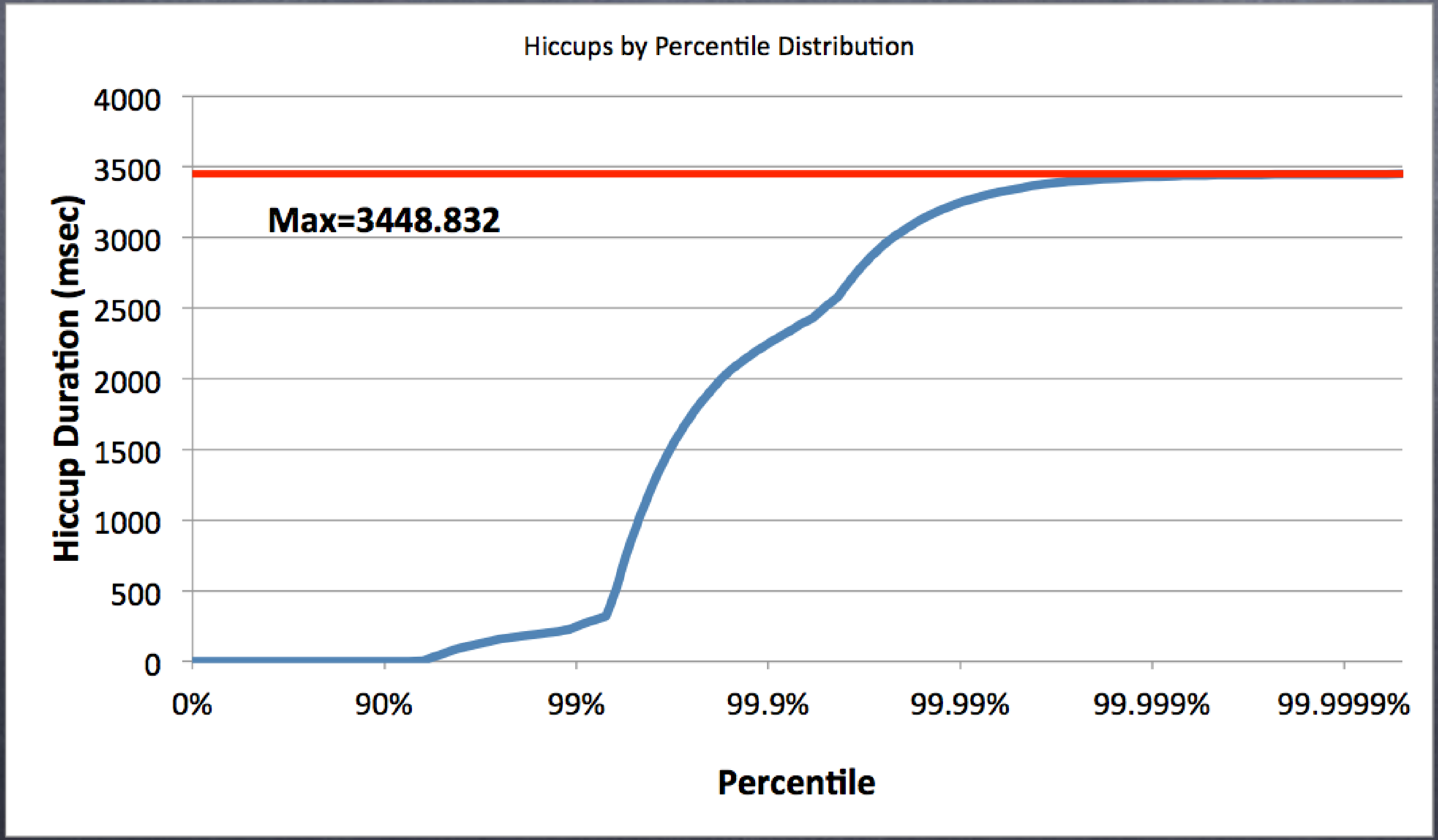
Optional SLA plotting



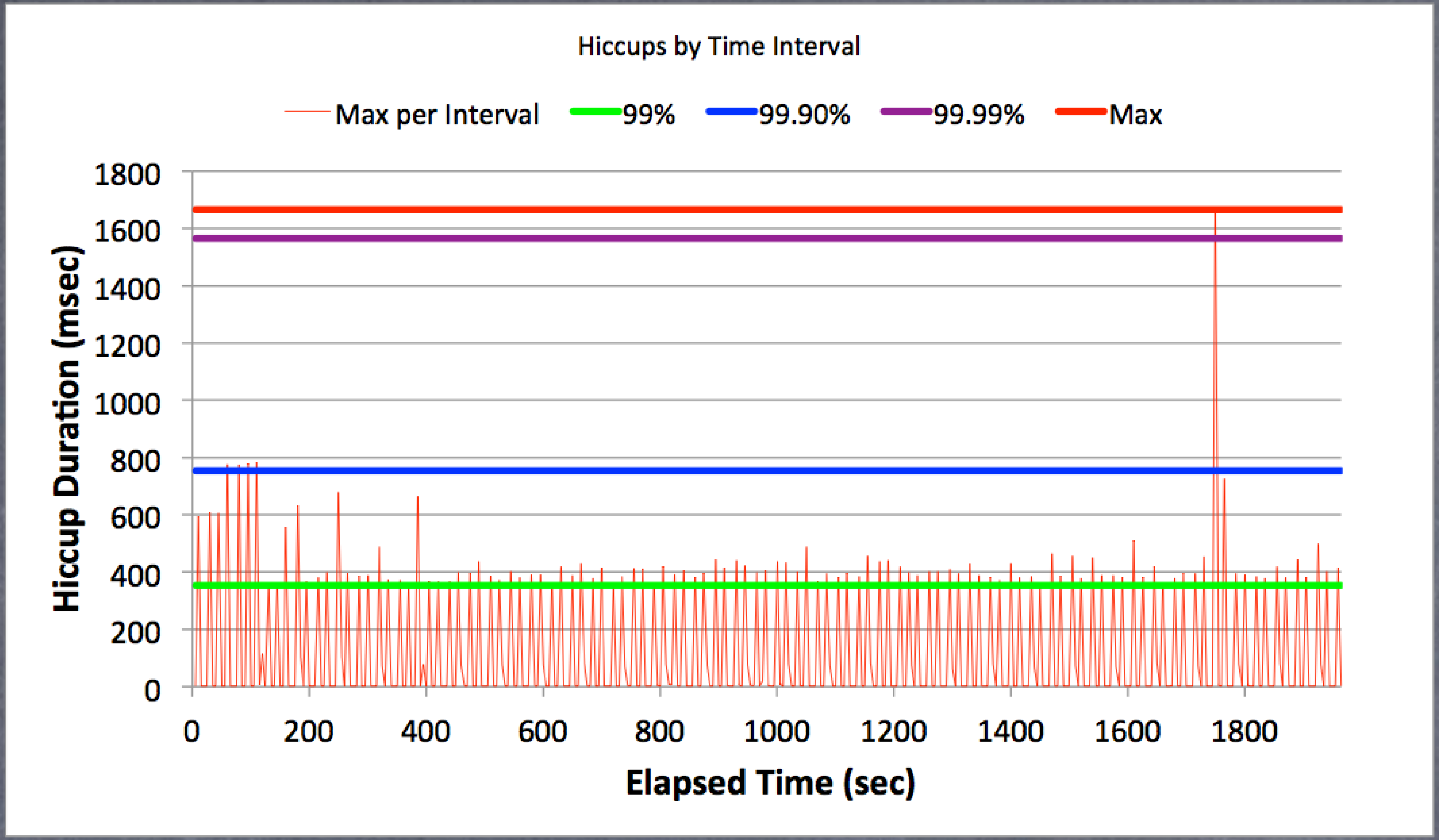
Hiccup duration at percentile levels

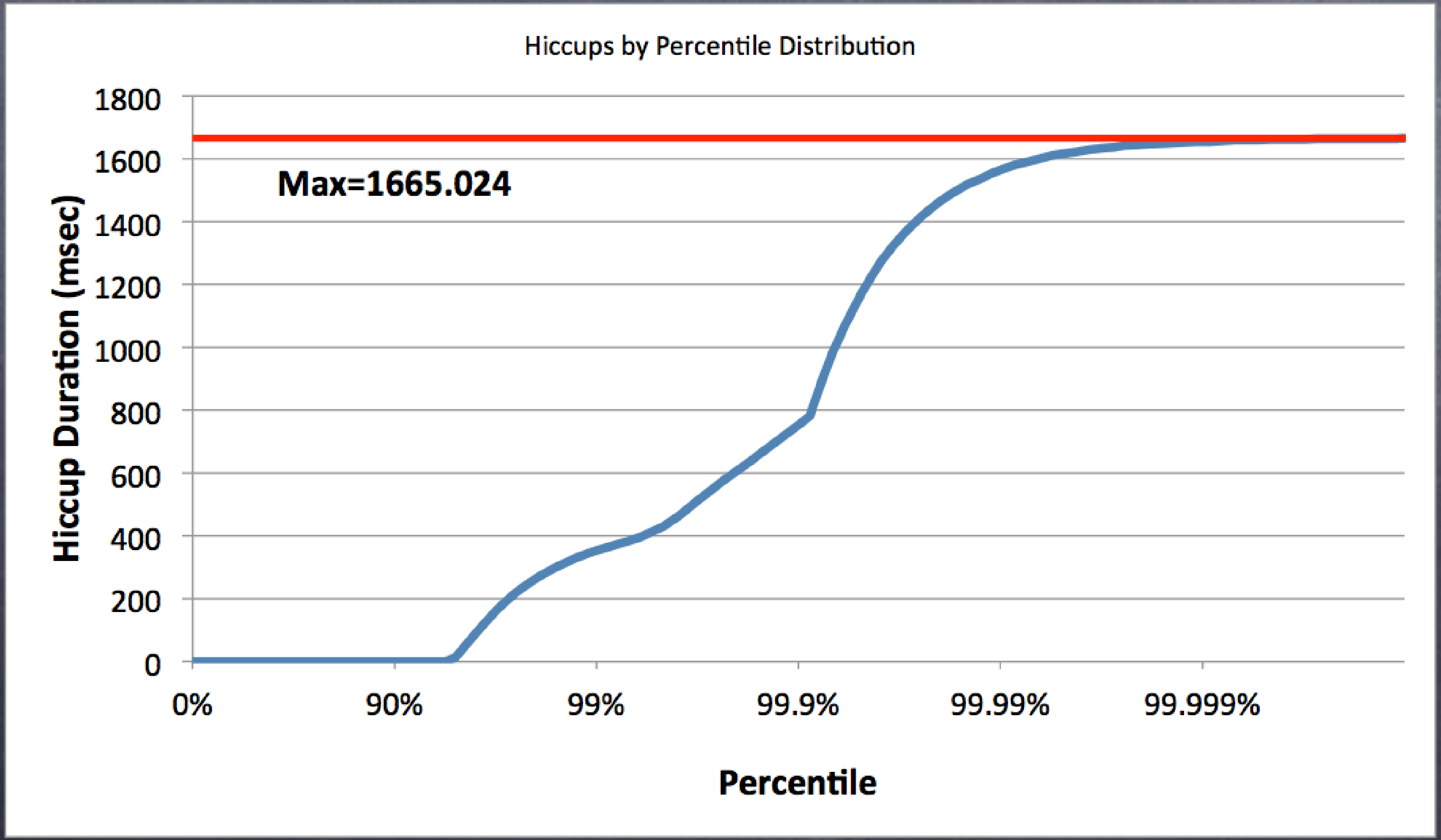
EHCache: 1GB data set under load



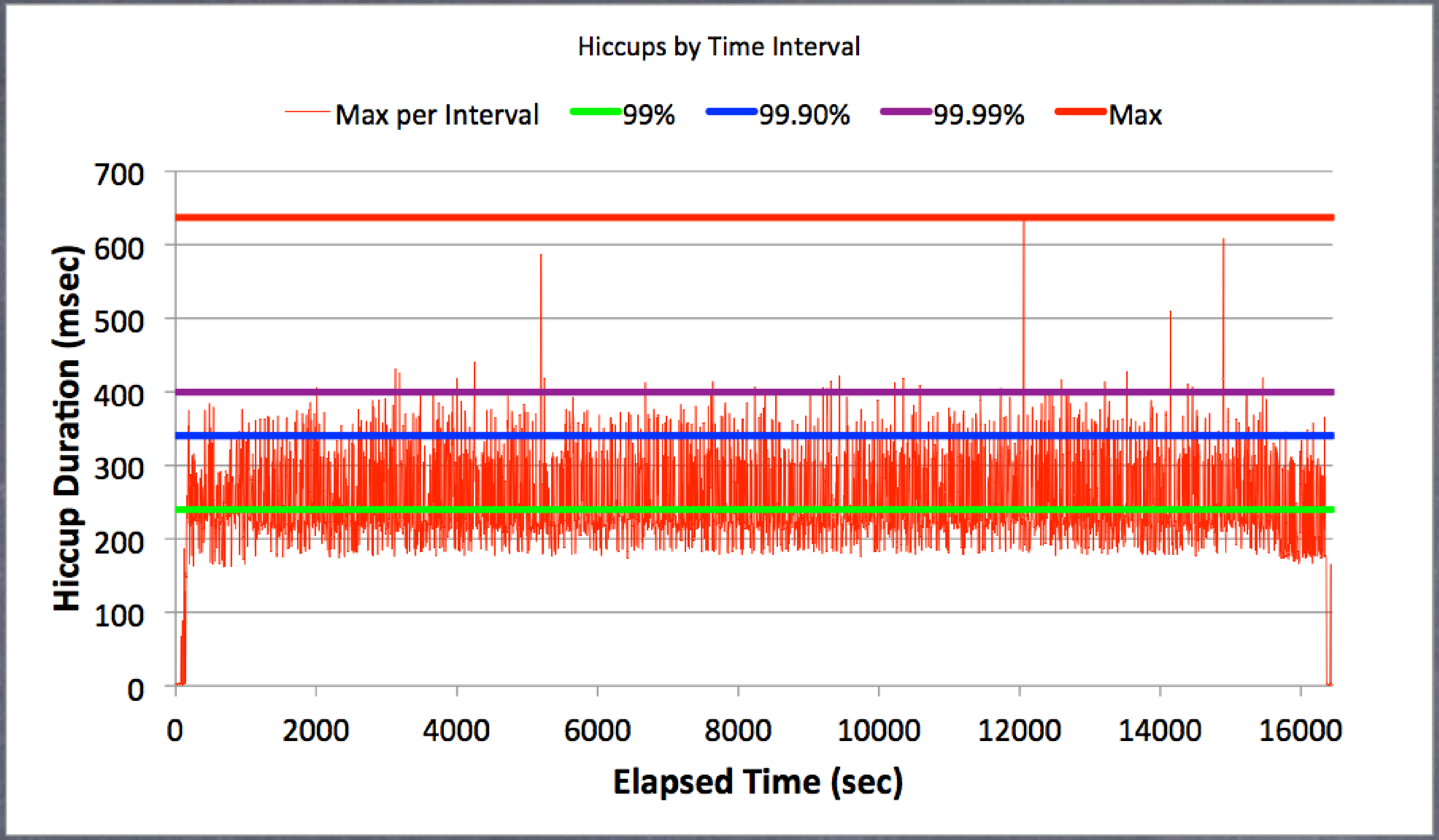


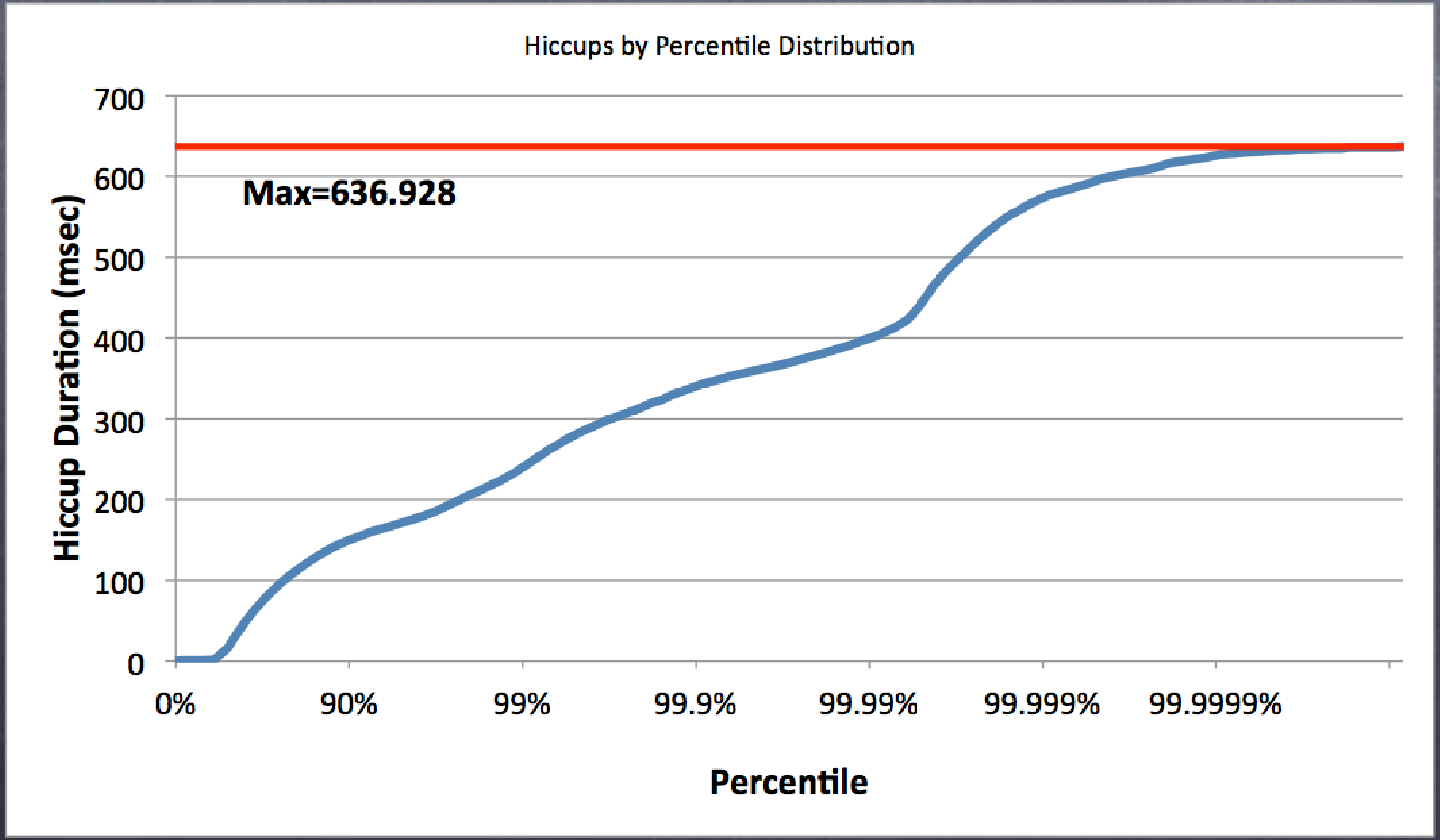
Telco Application





FiServ Pricing Application

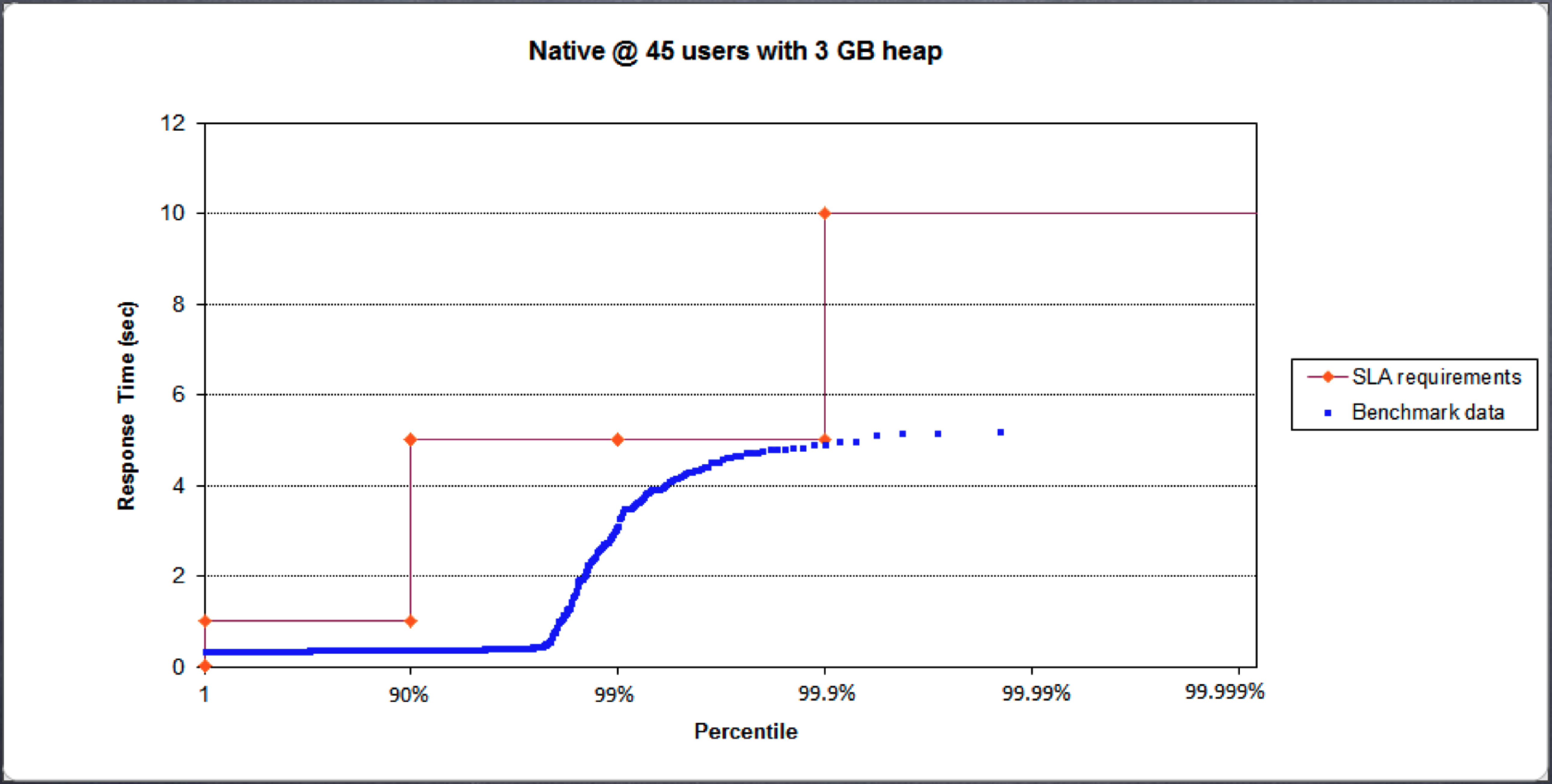




Sustainable Throughput: The throughput achieved while safely maintaining service levels

Unsustainable Throughout

Instance capacity test: “Fat Portal”
HotSpot CMS: Peaks at ~ 3GB / 45 concurrent users



* LifeRay portal on JBoss @ 99.9% SLA of 5 second response times

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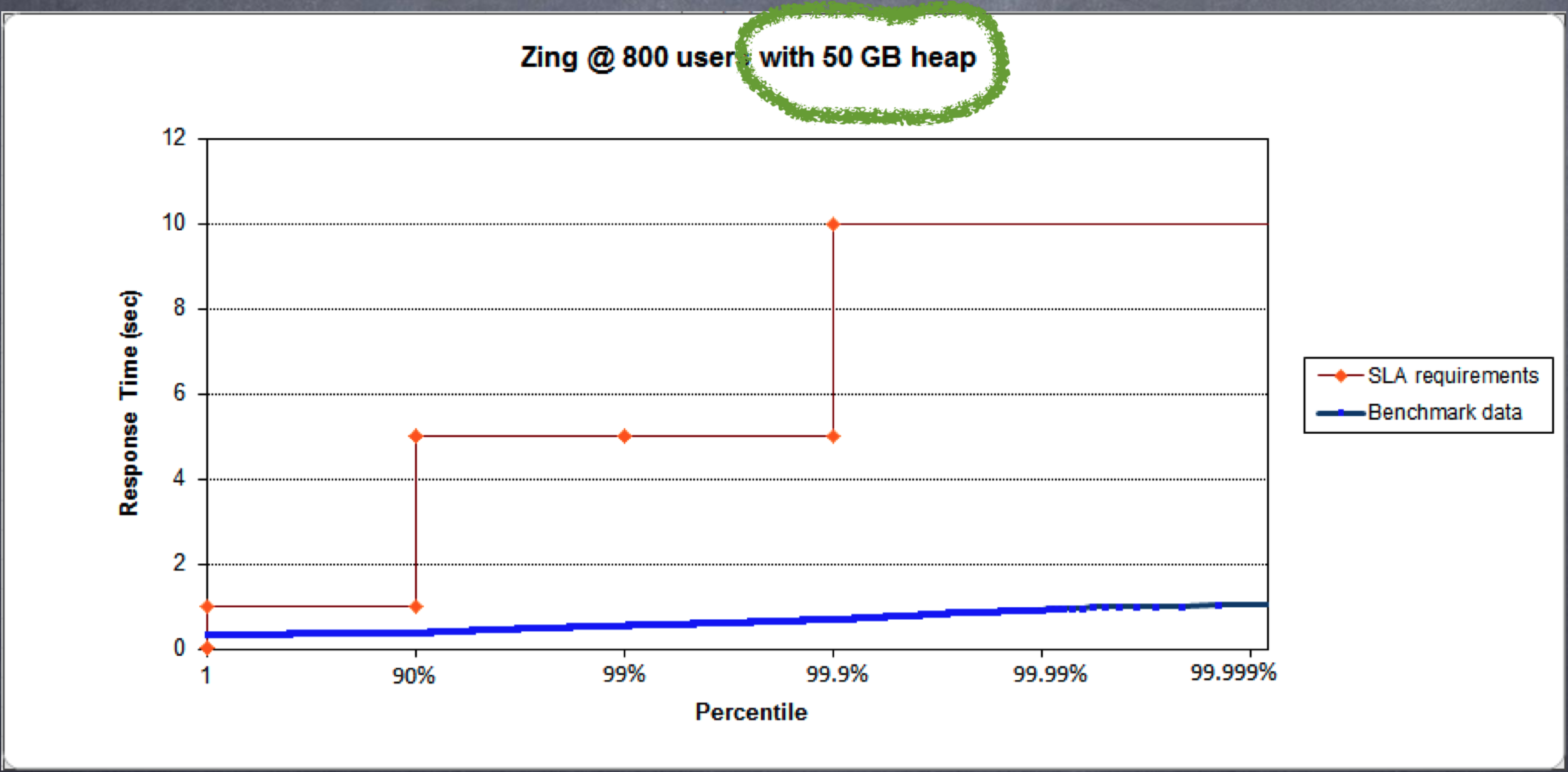
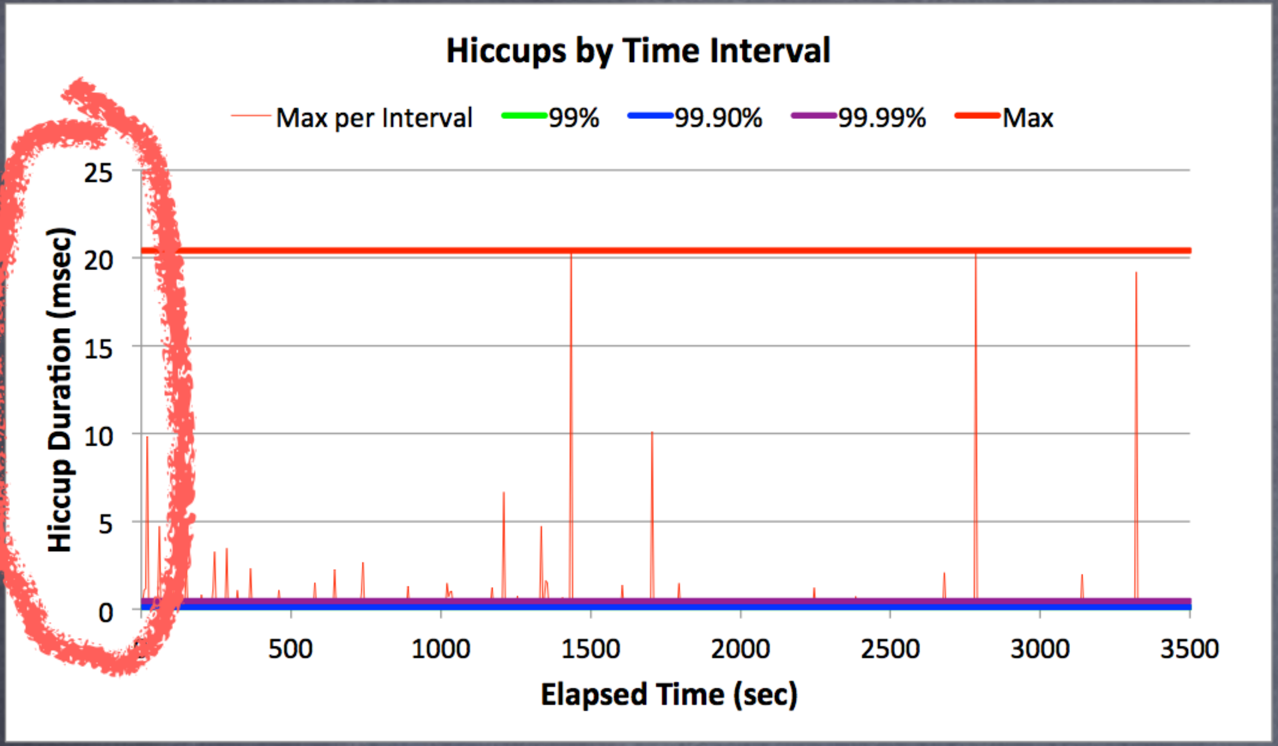
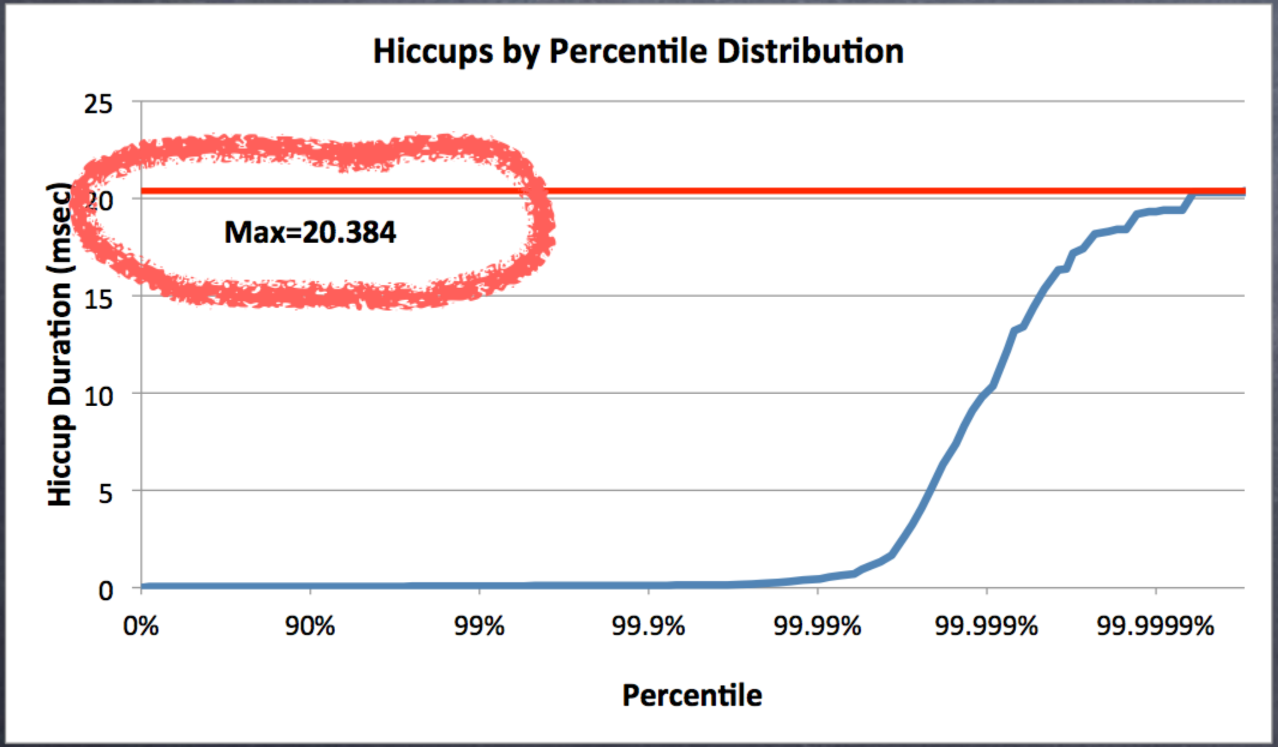
Instance capacity test: “Fat Portal”
C4: still smooth @ 800 concurrent users

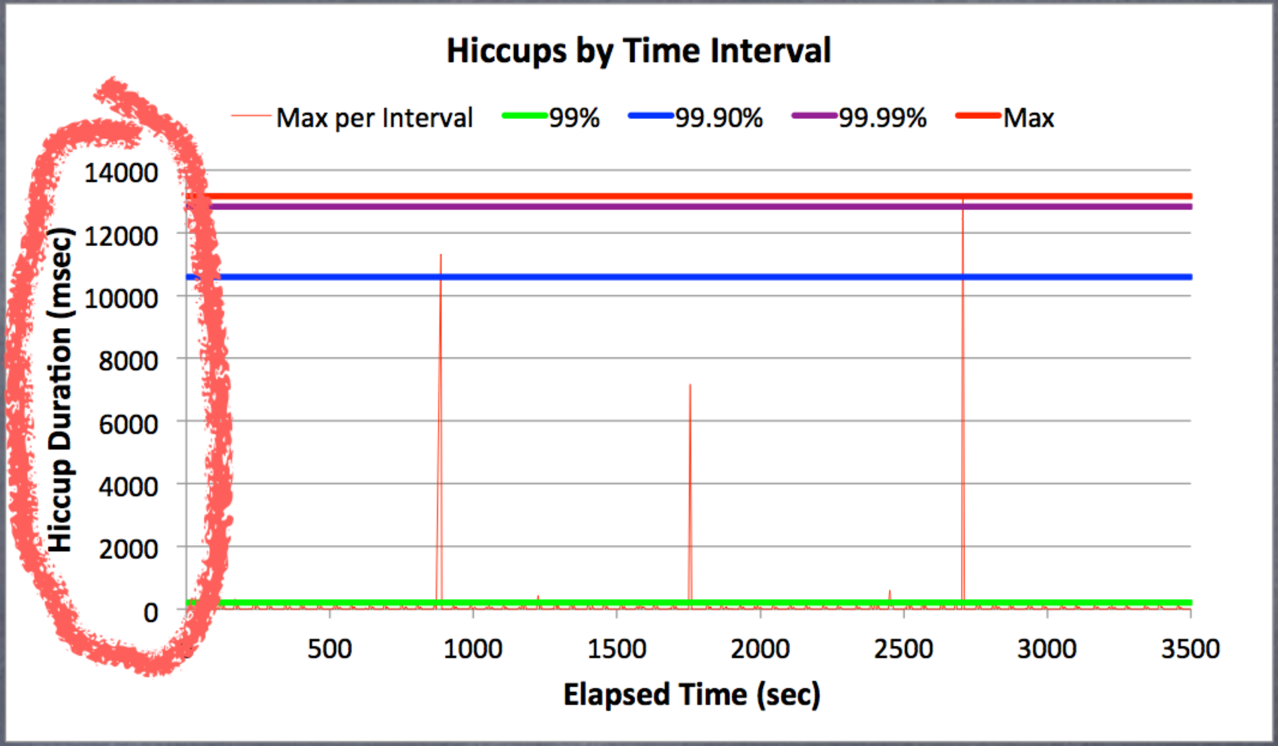


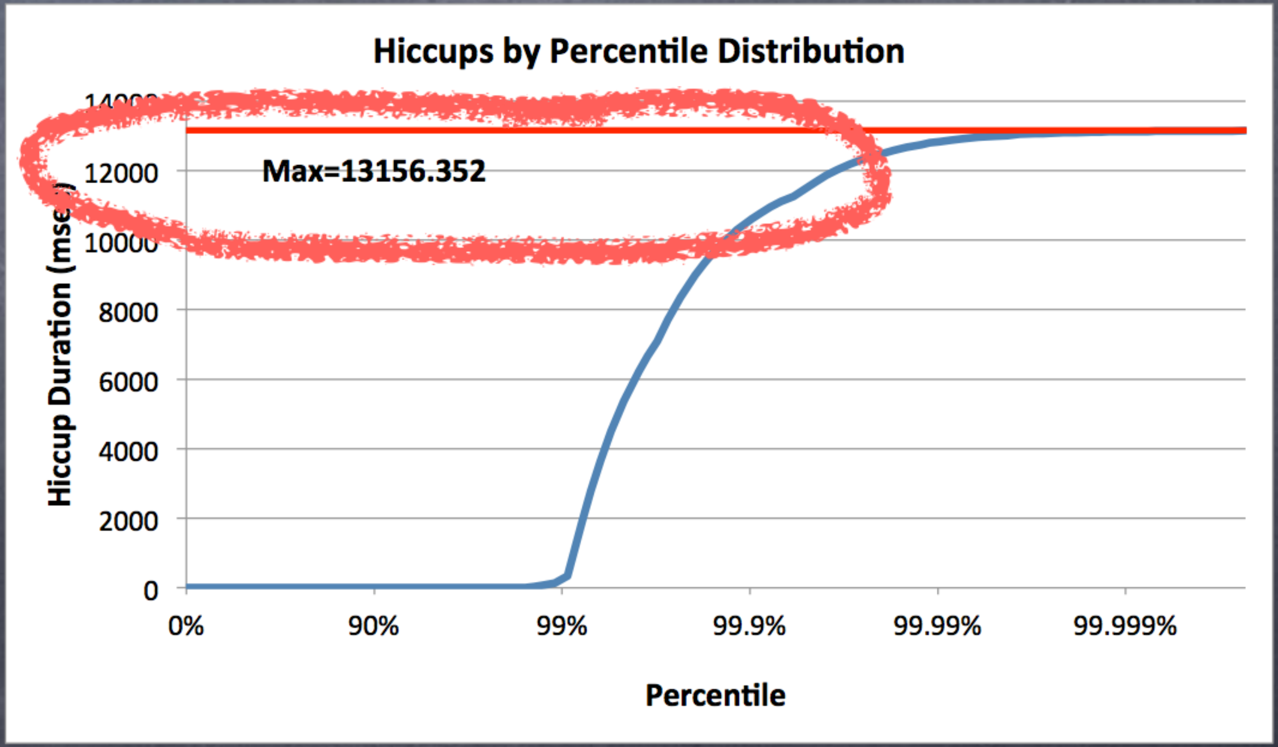
Zing 5, 1GB in an 8GB heap



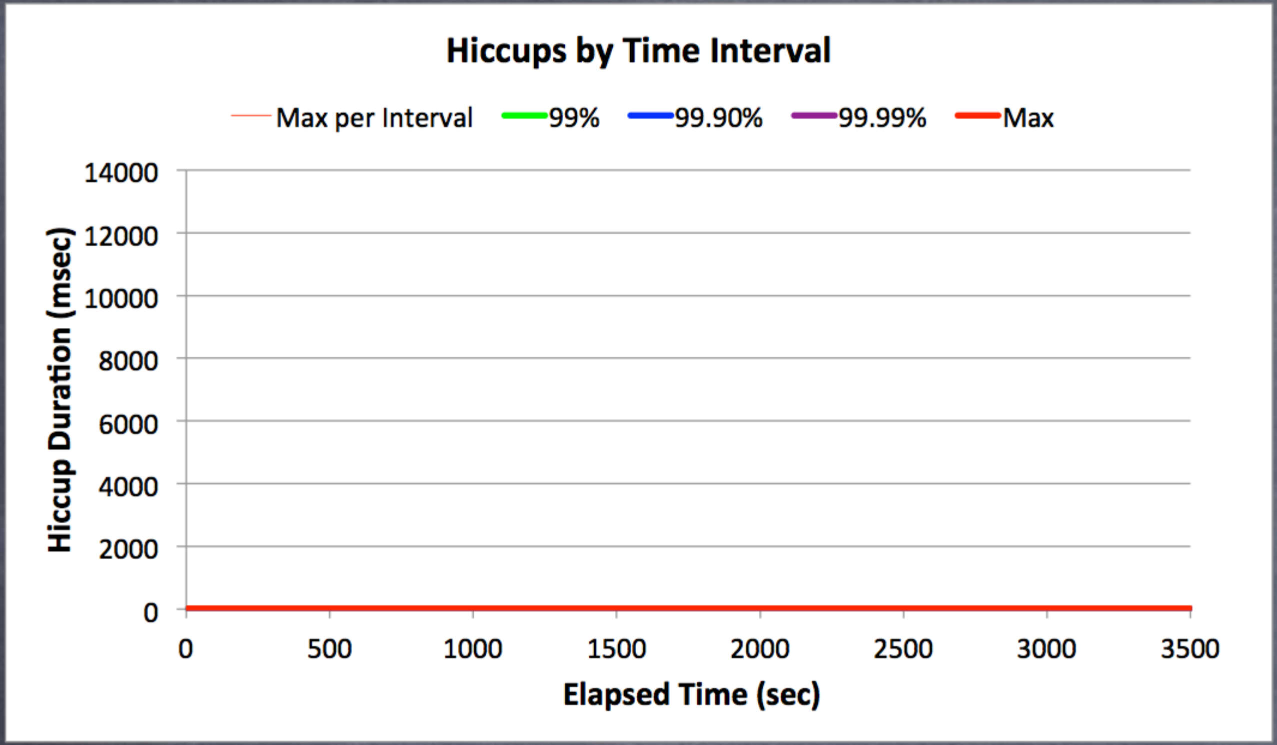


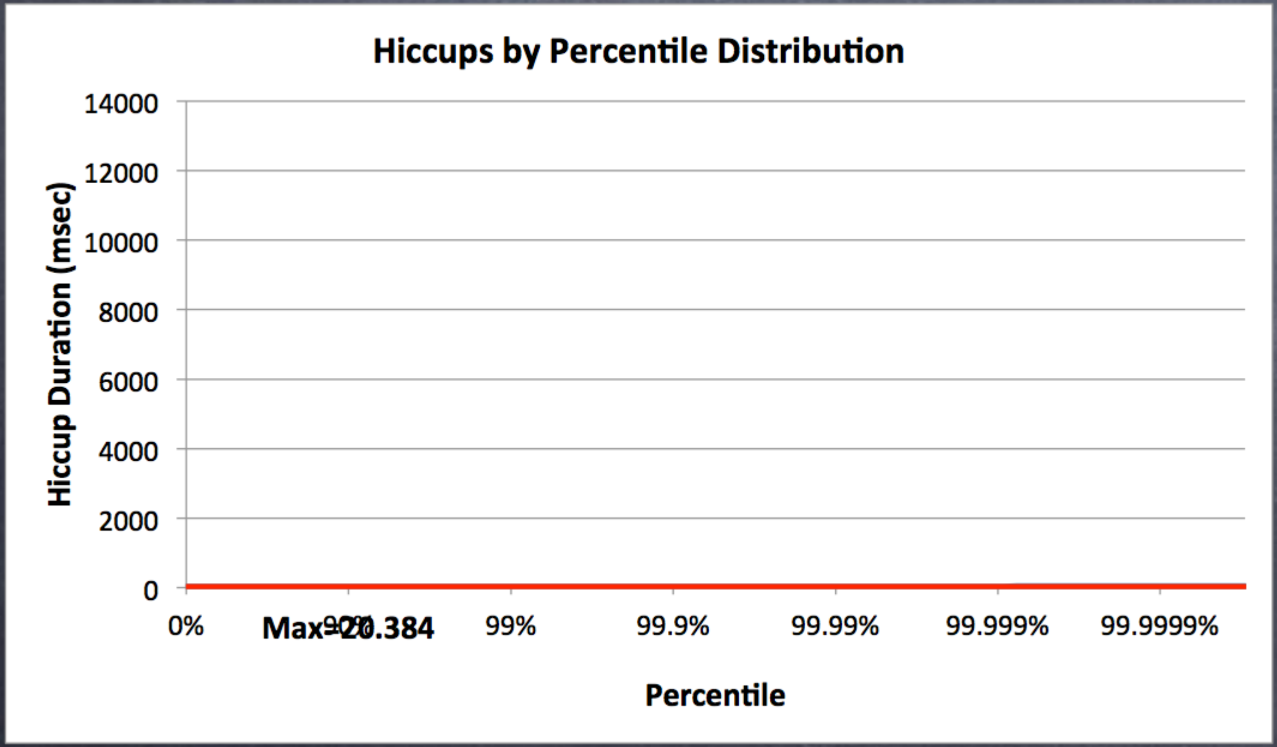
Oracle HotSpot CMS, 1GB in an 8GB heap





Zing 5, 1GB in an 8GB heap





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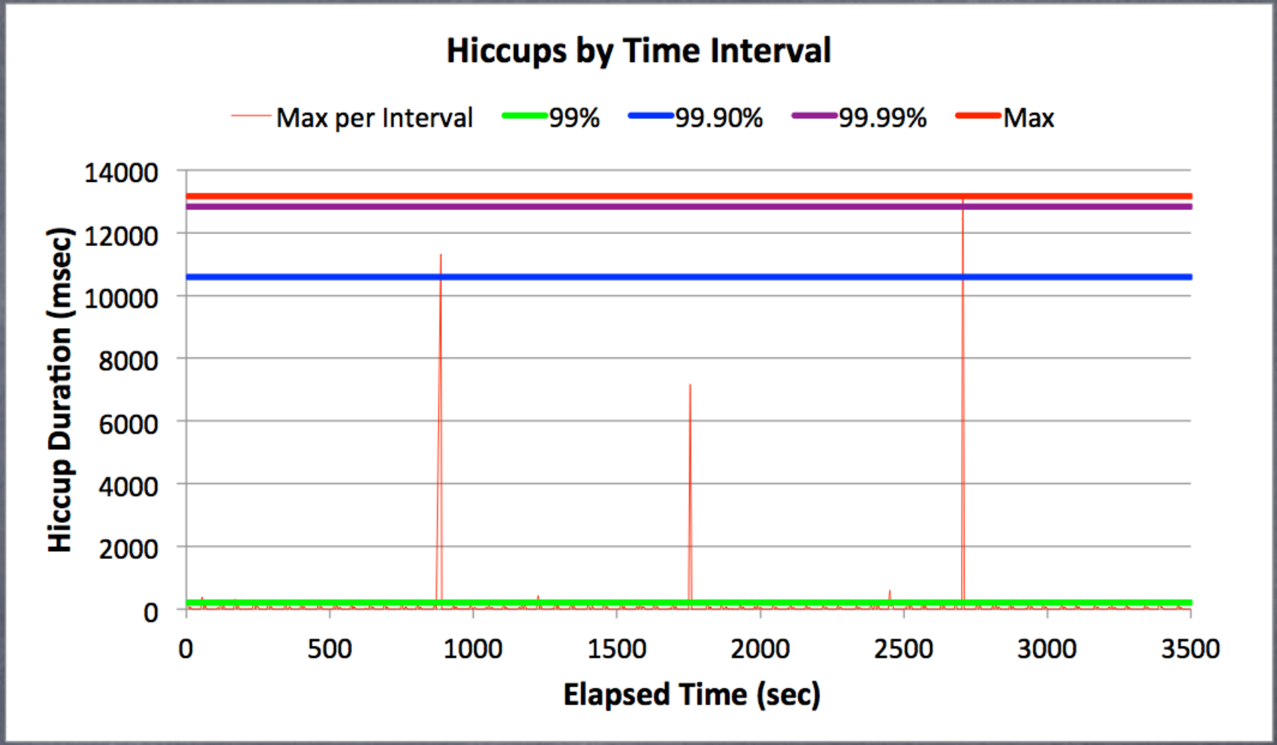
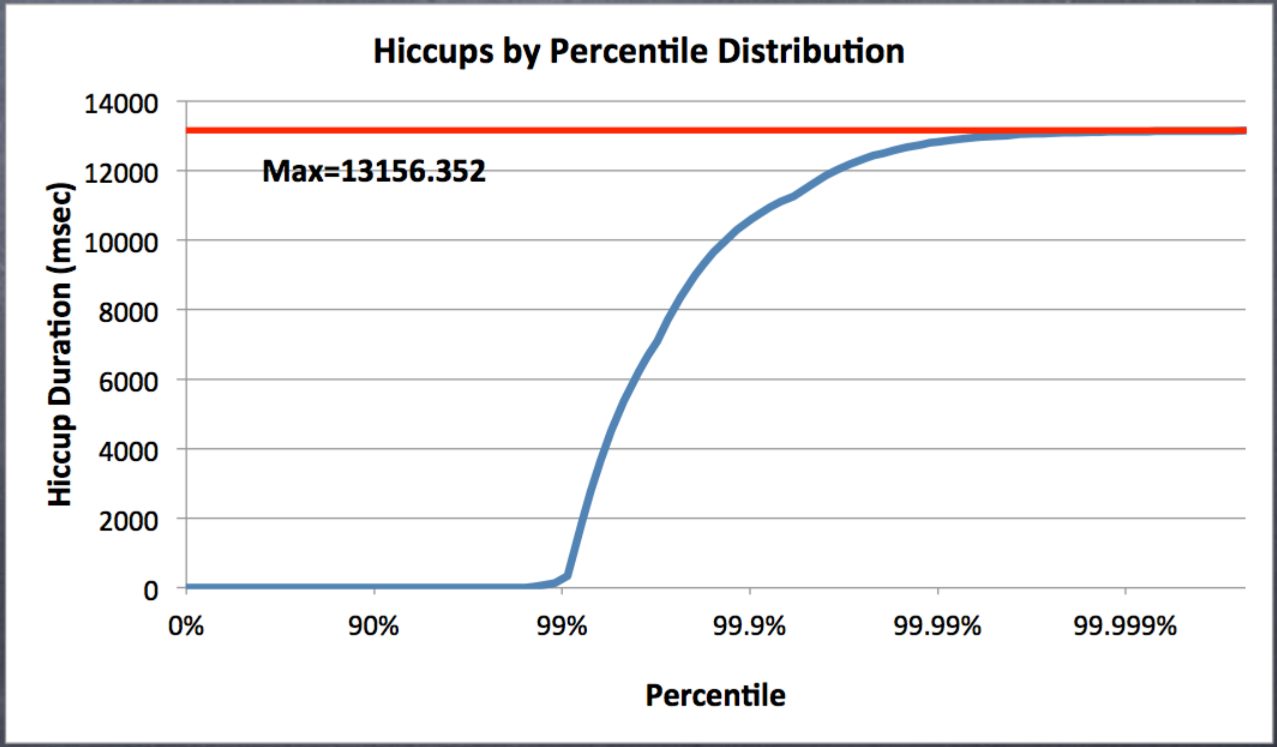




How is Azul's Java Platform Different?

- Same JVM standard -
  - Licensed JCK compliant JVM for JSE6 and JSE7. JSE 8 in flight.*
  - Derived from same base as Hotspot, fully Java compatible
    - passes Java Compatibility Kit (JCK) server-level compatibility (~53000 tests)
- A different approach
  - Garbage *is* good!
  - Designed with insight that worst case must eventually happen
- Unique values
  - **Highly scalable … 100s GB with consistent low pause times** – other JVMs will have longer "stop-the-world" pauses in proportion to size of JVM and memory allocation rate
  - **Elastic memory … insurance for JVMs to handle dynamic load** – unlike other JVMs which are rigidly tuned
  - **Collects New Garbage and Old Garbage concurrently with running application threads** … there is no "stop-the-world" for GC purposes (you will only see extremely short pause times to reach safepoints) – unlike other JVMs which will eventually stop-the-world.
  - **Compacts Memory concurrently with your application threads running** … Zing will move objects without "stop-the-world" or single-threading – which is a major issue with other JVMs
  - **Measuring pause times from FIRST thread stopped** (unlike other JVMs)
  - **Rich non-intrusive production visibility** with ZVision and ZVRobot
  - **WYTIWYG** (What You Test Is What You Get)

* Zing for JSE8 in dev
with JCK 8 in QA as of
today's talk

"We were originally designed for extremely large heaps, and some people use us in huge-data-set situations – which is why a typical 5GB or 10GB heap that challenges most JVMs is a walk in the park for Zing"

Some people have big problems to solve in the big data world and Zing doesn’t pause for GC

Tests were performed with varying live data set sizes, and a 250GB heap:

55 GB:

- Zing: 35 milliseconds; Hotspot G1: 357 seconds

110 GB:

- Zing: 75 milliseconds; Hotspot G1: 225 seconds

215 GB:

- Zing: 20 milliseconds; Hotspot G1: 1,055 seconds

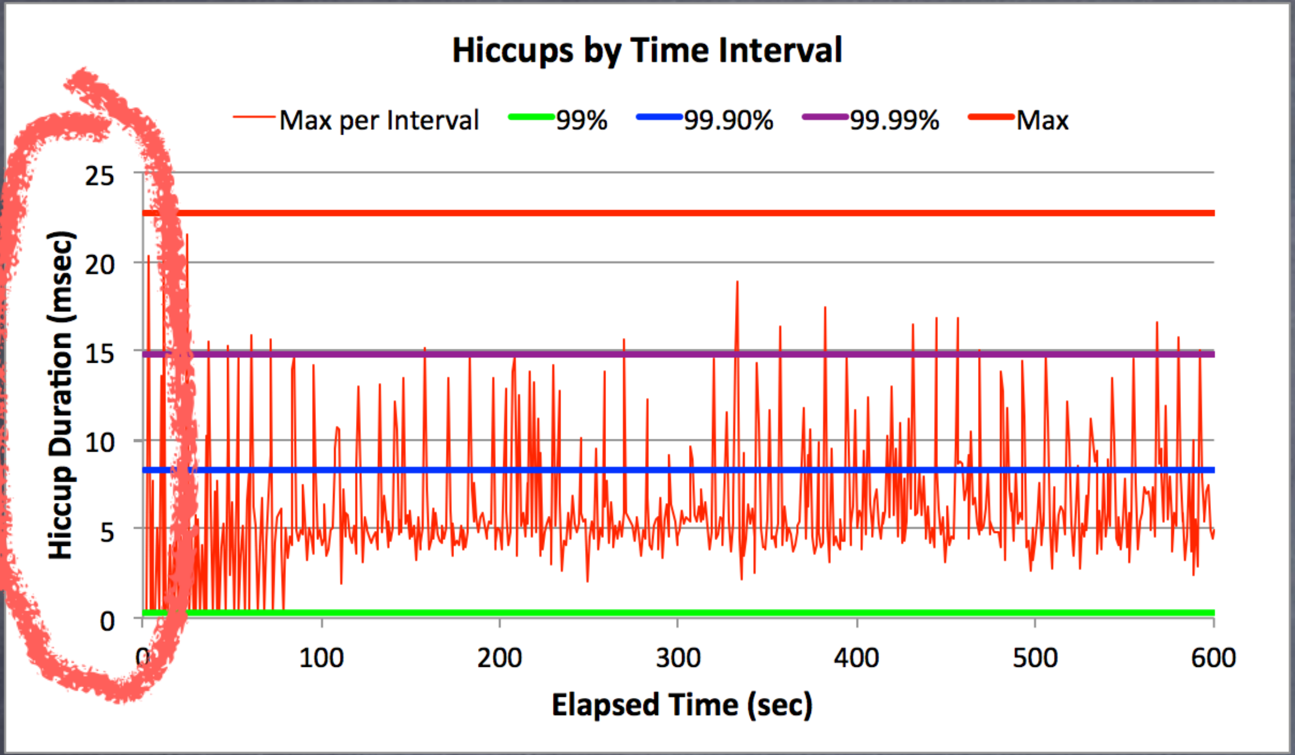
JavaOne 2012: Neil Ferguson, Causata:
CON4623 - Big RAM: How Java Developers Can Fully Exploit Massive Amounts of RAM

What you can expect (from Zing) in the low latency world

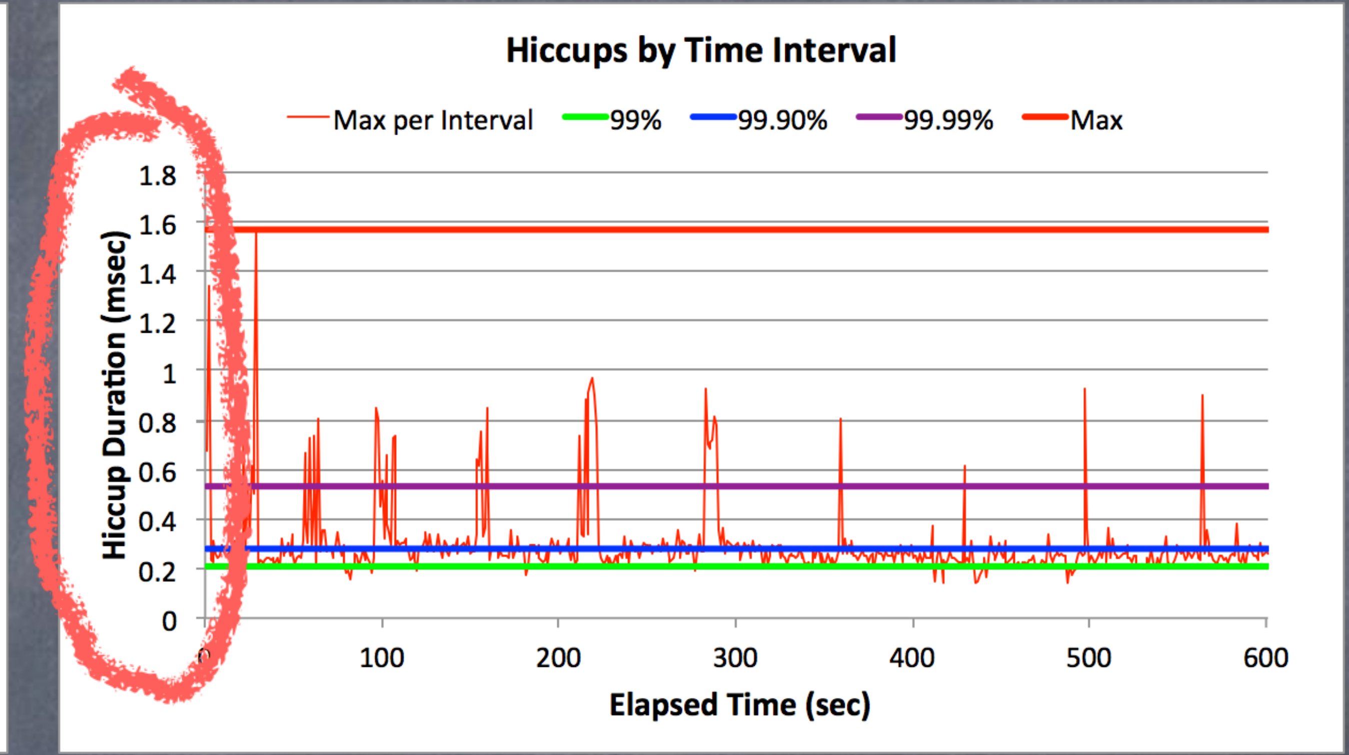
- Assuming individual transaction work is “short” (on the order of 1 msec), and assuming you don’t have 100s of runnable threads competing for 10 cores...
- “Easily” get your application to < 10 msec worst case
- With some tuning, 2-3 msec worst case
- Can go to below 1 msec worst case...
  - May require heavy tuning/tweaking
  - Mileage WILL vary

Oracle HotSpot (pure newgen)

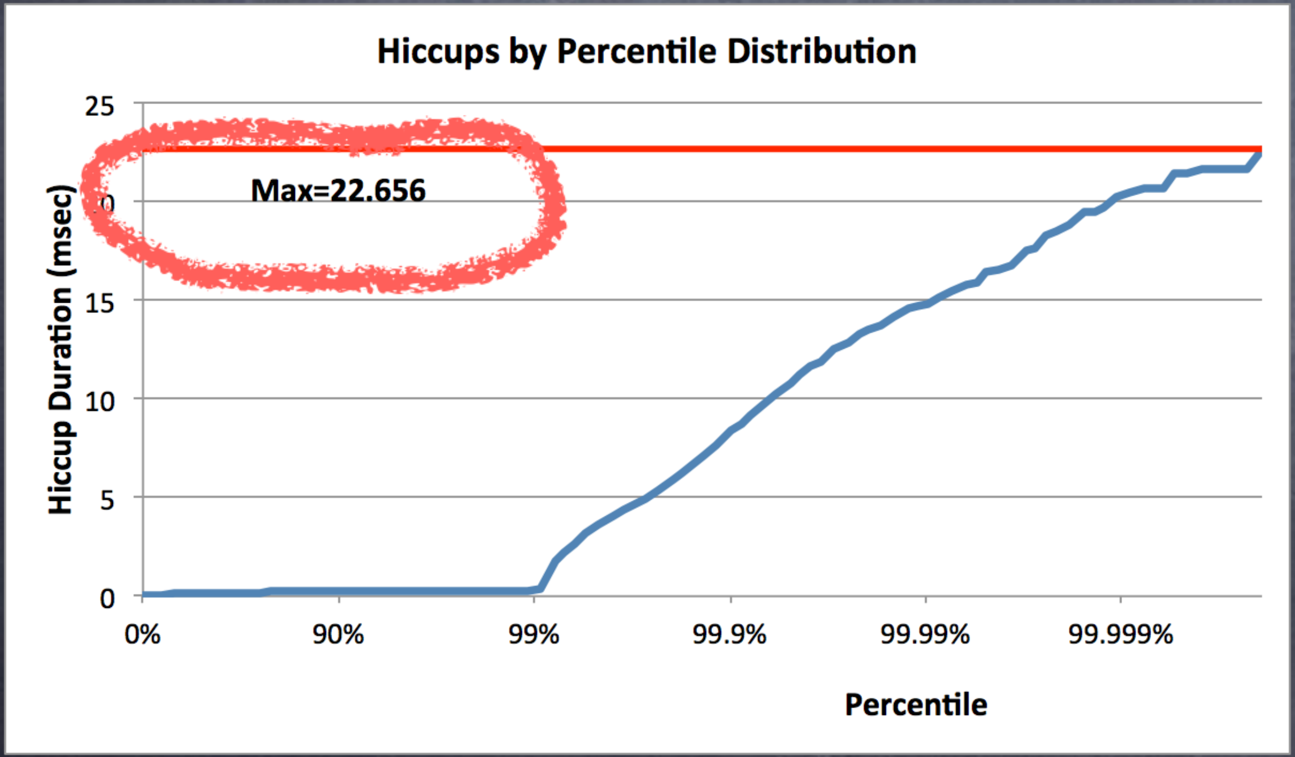
Zing



Hiccups by Time Interval

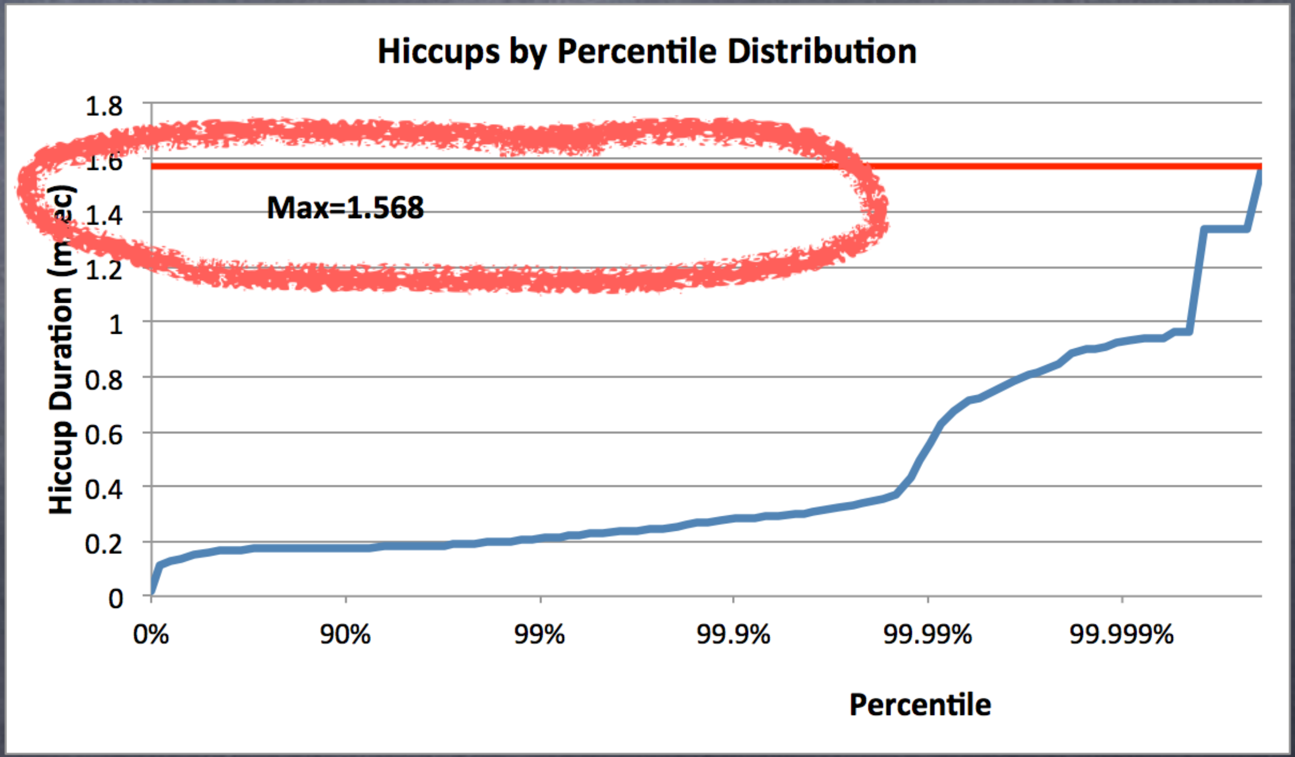


Hiccups by Time Interval



Hiccups by Percentile Distribution

Max=22.656



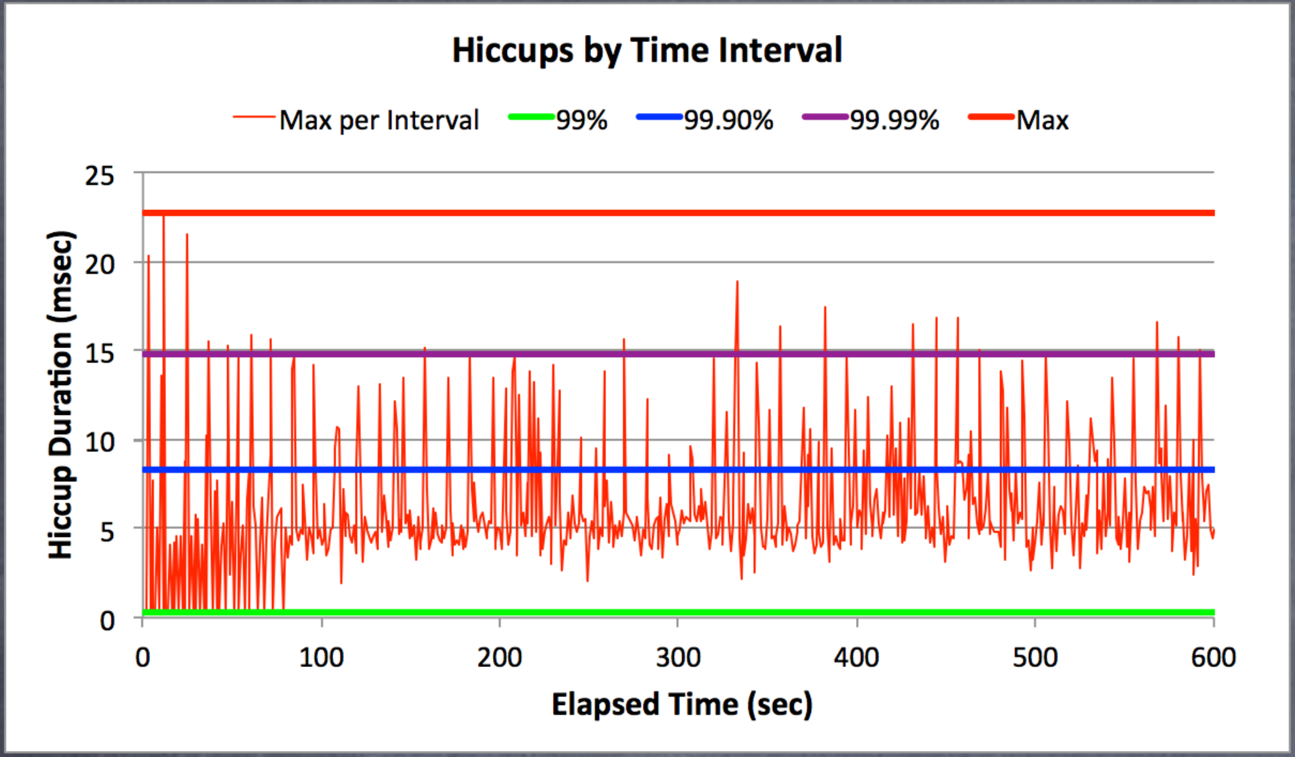
Hiccups by Percentile Distribution

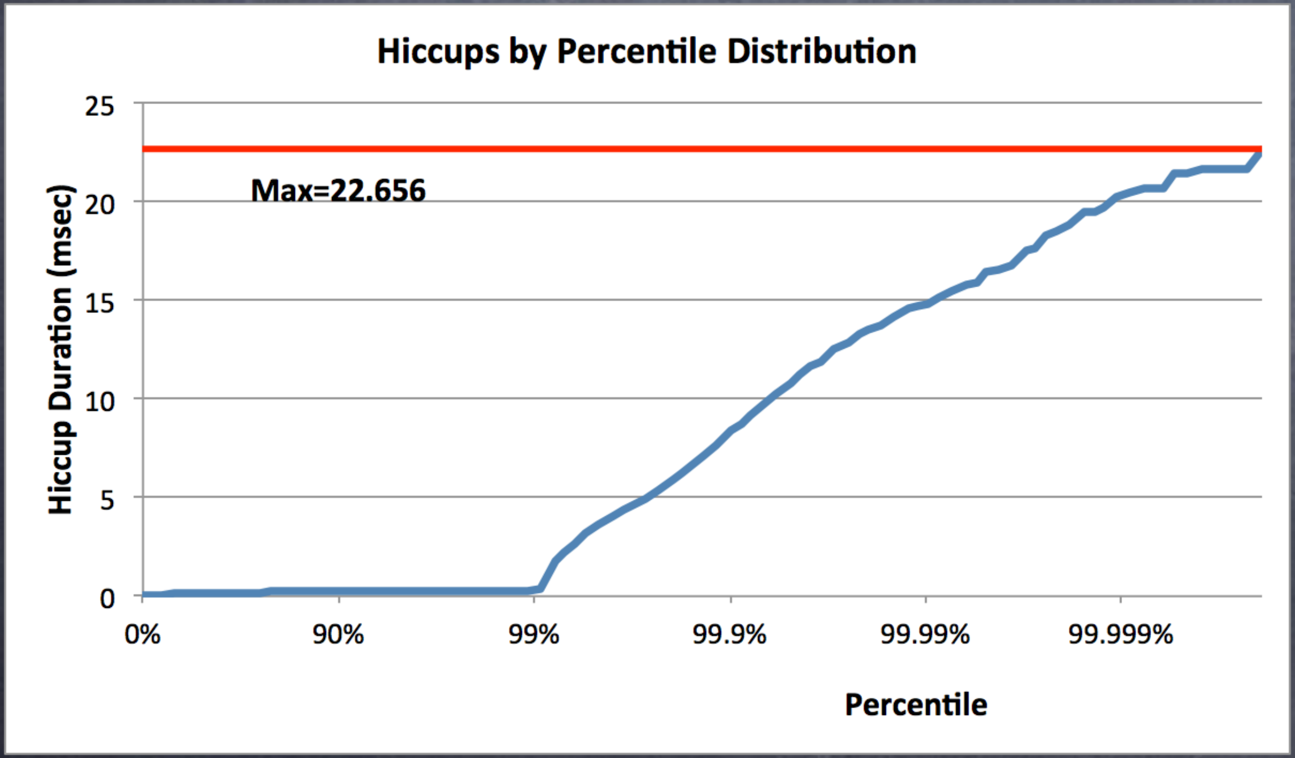
Max=1.568

Low latency trading application

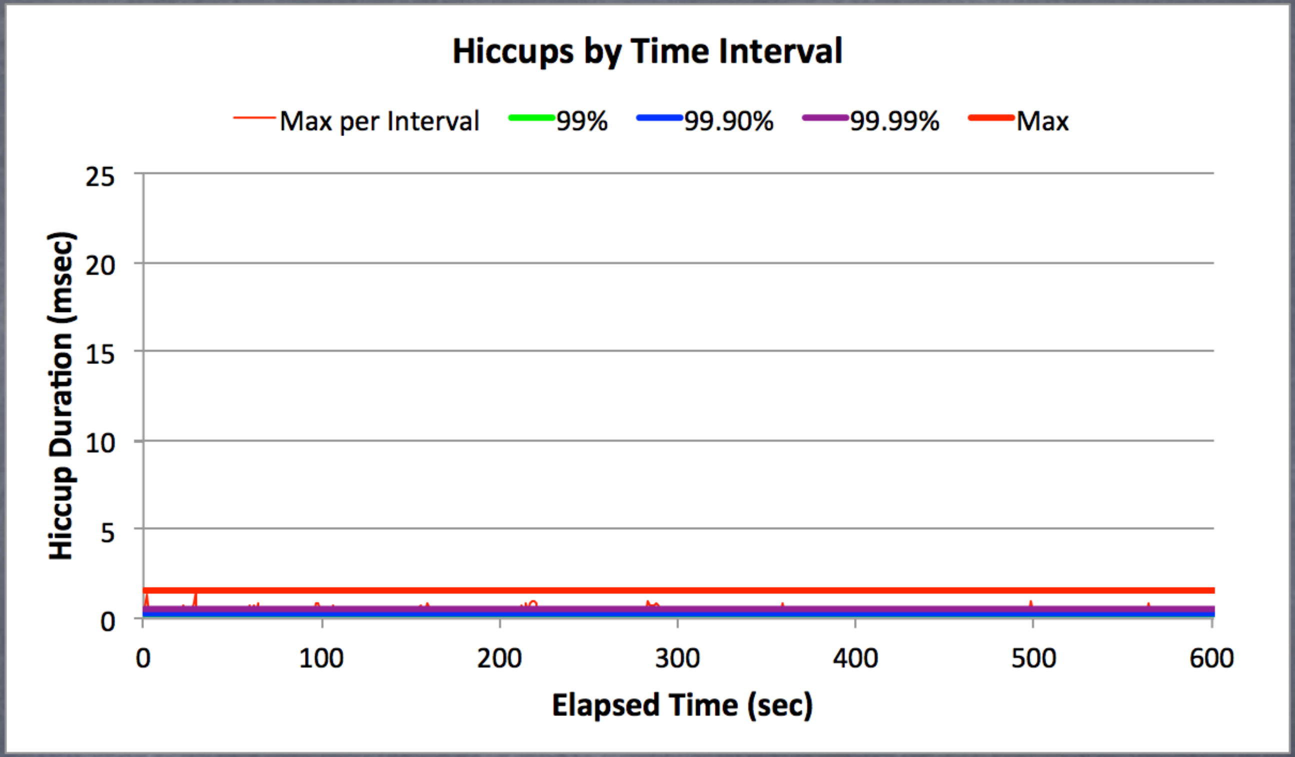
Low latency - Drawn to scale

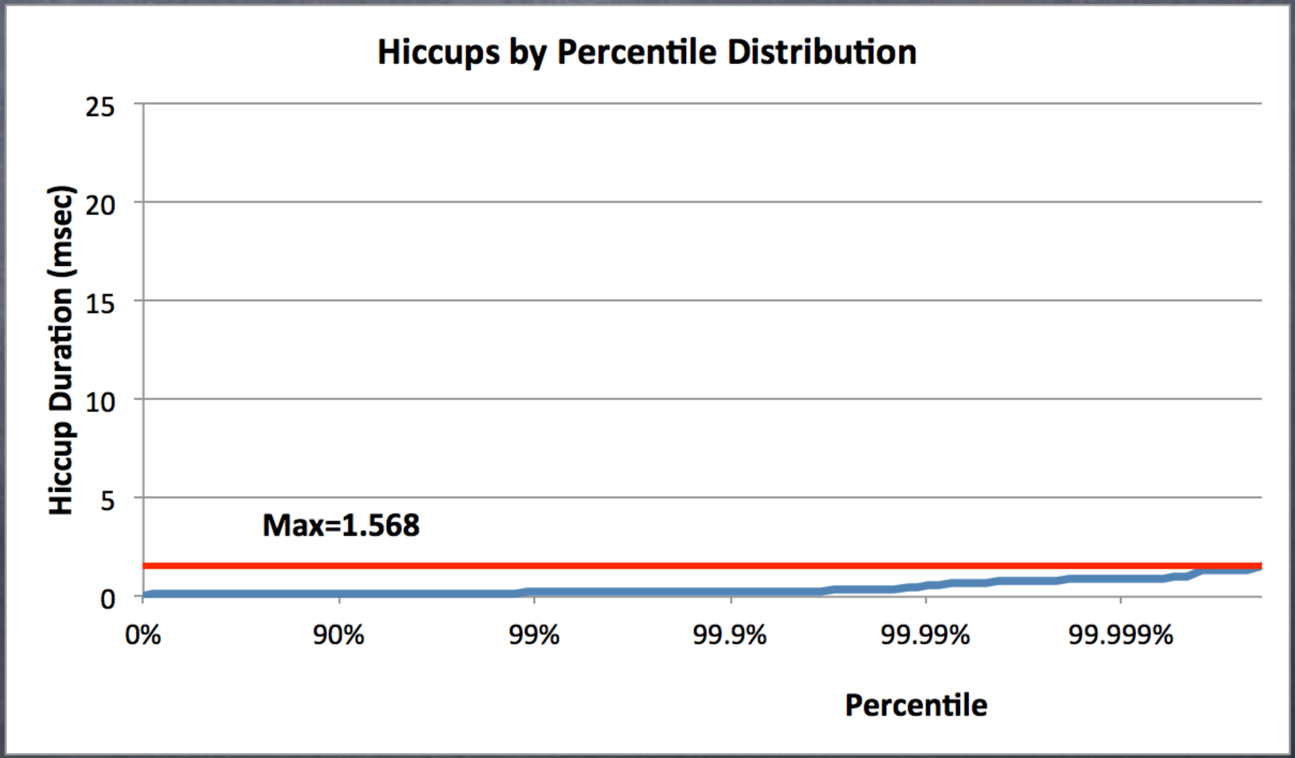
Oracle HotSpot (pure newgen)


Hiccups by Time Interval


Hiccups by Percentile Distribution

Zing


Hiccups by Time Interval


Hiccups by Percentile Distribution

Q & A

GC :

G. Tene, B. Iyengar and M. Wolf
C4: The Continuously Concurrent Compacting Collector
In Proceedings of the international symposium on Memory management, ISMM'11, ACM, pages 79-88

Jones, Richard; Hosking, Antony; Moss, Eliot (25 July 2011).
The Garbage Collection Handbook: The Art of Automatic Memory Management. CRC Press. ISBN 1420082795.

jHiccup:

http://www.azulsystems.com/dev_resources/jhiccup

Thanks for Attending

www.azulsystems.com

Grab a Shirt!

Take a card!

To contact the speaker email:
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Refer to PhillyJUG