# Understanding Java Garbage Collection

and what you can do about it

Gil Tene, CTO & co-Founder, Azul Systems

# This Talk's Purpose / Goals

- This talk is focused on GC education
- This is not a "how to use flags to tune a collector" talk
- 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...

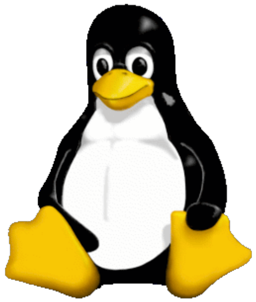
# About me: Gil Tene

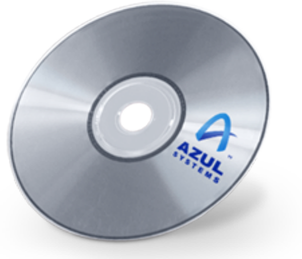
- co-founder, CTO @Azul Systems
- Have been working on a "think different" GC approaches since 2002
- Created Pauseless & C4 core GC algorithms (Tene, Wolf)
- A Long history building Virtual & Physical Machines, Operating Systems, Enterprise apps, etc...


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

# 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





# High level agenda

- GC fundamentals and key mechanisms
- Some GC terminology & metrics
- Classifying currently available collectors
- The "Application Memory Wall" problem
- The C4 collector: What an actual solution looks like...

# 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?

# Why should you care?

# The story of the good little architect

- A good architect must, first and foremost, be able to impose their architectural choices on the project...
- Early in Azul's concurrent collector days, we encountered an application exhibiting 18 second pauses
  - Upon investigation, we found the collector was performing 10s of milliions of object finalizations per GC cycle
    - *We have since made reference processing fully concurrent...
- Every single class written in the project has a finalizer
  - The only work the finalizers did was nulling every reference field
- The right discipline for a C++ ref-counting environment
  - The wrong discipline for a precise garbage collected environment

# Trying to solve GC problems in application architecture is live throwing knives

- You probably shouldn't do it blindfolded
- It takes practice and understanding to get it right
- 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:
  - Object pooling
  - Off heap storage
  - Distributed heaps
  - ...
  - (In most cases, you end up building your own garbage collector)

# Most 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
  - ...

# Some GC Terminology

# A Basic Terminology example: What is a concurrent collector?

- A Concurrent Collector performs garbage collection work concurrently with the application's own execution

- A Parallel Collector uses multiple CPUs to perform garbage collection

# Classifying a collector's operation

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

# Precise vs. Conservative Collection

- A Collector is Conservative if it is unaware of all object references at collection time, or is unsure about whether a field is a reference or not
- A Collector is Precise if it can fully identify and process all object references are at the time of collection
  - A collector MUST be precise in order to move objects
  - The COMPILERS need to produce a lot of information (oopmaps)
- All commercial server JVMs use precise collectors
  - All commercial server JVMs use some form of a moving collector

# Safepoints

- A GC Safepoint is a point or range in a thread's execution where the collector can identify all the references in that thread's execution stack
  - "Safepoint" and "GC Safepoint" are often used interchangeably
  - But there are other types of safepoints, including ones that require more information than a GC safepoint does (e.g. deoptimization)
- "Bringing a thread to a safepoint" is the act of getting a thread to reach a safepoint and not execute past it
  - Close to, but not exactly the same as "stop at a safepoint"
    - e.g. JNI: you can keep running in, but not past the safepoint
  - Safepoint opportunities are (or should be) frequent
- In a Global Safepoint all threads are at a Safepoint

# What's common to all precise GC mechanisms?

- Identify the live objects in the memory heap
- Reclaim resources held by dead objects
- Periodically relocate live objects

- Examples:
  - Mark/Sweep/Compact (common for Old Generations)
  - Copying collector (common for Young Generations)

# Mark (aka “Trace”)

- Start from “roots” (thread stacks, statics, etc.)
- “Paint” anything you can reach as “live”
- At the end of a mark pass:
  - all reachable objects will be marked “live”
  - all non-reachable objects will be marked “dead” (aka “non-live”).

- Note: work is generally linear to “live set”

# Sweep

- Scan through the heap, identify “dead” objects and track them somehow
  - (usually in some form of free list)

- Note: work is generally linear to heap size

# 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

- 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"

# Mark/Sweep/Compact, Copy, Mark/Compact

- Copy requires 2x the max. live set to be reliable
- Mark/Compact [typically] requires 2x the max. live set in order to fully recover garbage in each cycle
- Mark/Sweep/Compact only requires 1x (plus some)
- Copy and Mark/Compact are linear only to live set
- Mark/Sweep/Compact linear (in sweep) to heap size
- Mark/Sweep/(Compact) may be able to avoid some moving work
- Copying is [typically] “monolithic”

# Generational Collection

- 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

# Generational Collection

- Requires a "Remembered set": a way to track all references into the young generation from the outside
- Remembered set is also part of "roots" for young generation collection
- No need for 2x the live set: Can "spill over" to old gen
- Usually want to keep surviving objects in young generation for a while before promoting them to the old generation
  - Immediate promotion can dramatically reduce gen. filter efficiency
  - Waiting too long to promote can dramatically increase copying work

# How does the remembered set work?

- Generational collectors require a "Remembered set": a way to track all references into the young generation from the outside
- Each store of a NewGen reference into and OldGen object needs to be intercepted and tracked
- Common technique: "Card Marking"
  - A bit (or byte) indicating a word (or region) in OldGen is "suspect"
- Write barrier used to track references
  - Common technique (e.g. HotSpot): blind stores on reference write
  - Variants: precise vs. imprecise card marking, conditional vs. non-conditional

# The typical combos in commercial server JVMS

- Young generation <u>usually</u> uses a copying collector
- Young generation is <u>usually</u> monolithic, stop-the-world

- Old generation <u>usually</u> uses Mark/Sweep/Compact
- Old generation may be STW, or Concurrent, or mostly-Concurrent, or Incremental-STW, or mostly-Incremental-STW

# 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 heap
  - Moves 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

# Empty memory and CPU/throughput

# Two Intuitive limits

- If we had infinite empty memory, we would never have to collect, and GC would take 0% of the CPU time
- 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
- 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
- For both Copy and Mark/Compact collectors, the amount of work per cycle is linear to live set
- 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
- A Copy or Mark/Compact collector's efficiency 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 Mark/Sweep/Compact collectors that pause for sweeping, more empty memory means less frequent but LARGER pauses

# Some non-monolithic-STW stuff

# Concurrent Marking

- Mark all reachable objects as "live", but object graph is "mutating" under us.
- Classic concurrent marking race: mutator may move reference that has not yet been seen by the marker into an object that has already been visited
  - If not intercepted or prevented in some way, will corrupt the heap
- Example technique: track mutations, multi-pass marking
  - Track reference mutations during mark (e.g. in card table)
  - Re-visit all mutated references (and track new mutations)
  - When set is "small enough", do a STW catch up (<u>mostly</u> concurrent)
- Note: work grows with mutation rate, may fail to finish

# Incremental Compaction

- Track cross-region remembered sets (which region points to which)
- To compact a single region, only need to scan regions that point into it to remap all potential references
- identify regions sets that fit in limited time
  - Each such set of regions is a Stop-the-World increment
  - Safe to run application between (but not within) increments
- Note: work can grow with the square of the heap size
  - The number of regions pointing into a single region is generally linear to the heap size (the number of regions in the heap)

# Delaying the inevitable

- 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
  - 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

# Classifying common collectors

# The typical combos in commercial server JVMS

- Young generation usually uses a copying collector
  - Young generation is usually monolithic, stop-the-world
- Old generation usually uses a Mark/Sweep/Compact collector
  - Old generation may be STW, or Concurrent, or mostly-Concurrent, or Incremental-STW, or mostly-Incremental-STW

# 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.

# The “Application Memory Wall”

# 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?

# Reality check: servers in 2011

- Retail prices, major web server store (US $, Oct. 2011)

| | |
|---|---|
| 24 vCore, 96GB server | ≈ $5K |
| 32 vCore, 256GB server | ≈ $16K |
| 64 vCore, 512GB server | ≈ $30K |
| 80 vCore, 1TB server | ≈ $63K |

- Cheap (≈ $1.5/GB/Month), and roughly linear to ~1TB
- 10s to 100s of GB/sec of memory bandwidth

# The Application Memory Wall
# A simple observation:

- Application instances appear to be unable to make effective use of modern server memory capacities

- The size of application instances as a % of a server's capacity is rapidly dropping

# How much memory do applications need?

- "640KB ought to be enough for anybody"

WRONG!

"I've said some stupid things and some wrong things, but not that. No one involved in computers would ever say that a certain amount of memory is enough for all time …" - Bill Gates, 1996

- So what's the right number?

6,400K?
64,000K?
640,000K?
6,400,000K?
64,000,000K?

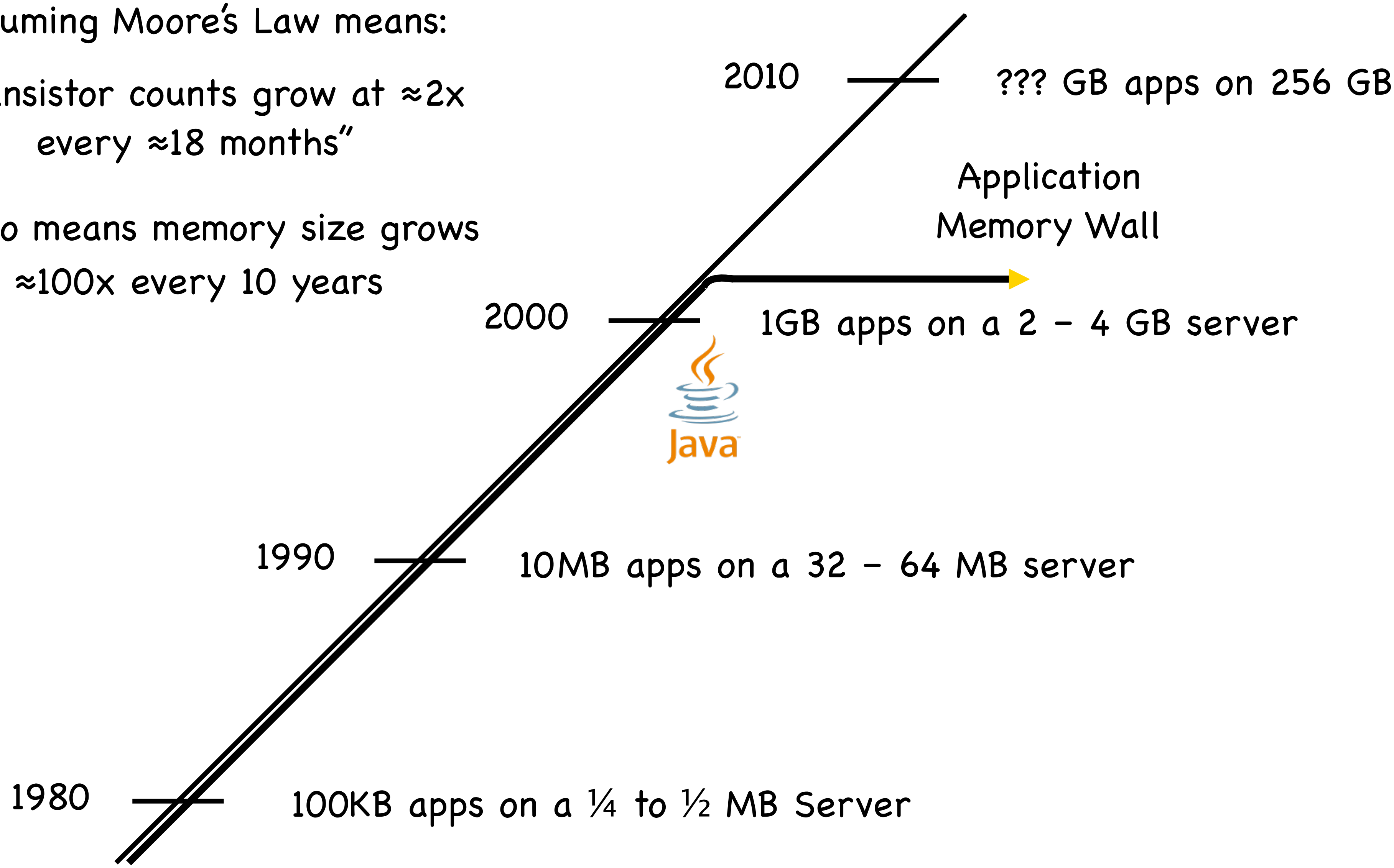
- There is no right number
- Target moves at 50x-100x per decade

# "Tiny" application history

Assuming Moore's Law means:

"transistor counts grow at ≈2x every ≈18 months"

It also means memory size grows ≈100x every 10 years




"Tiny": would be "silly" to distribute

# What is causing the Application Memory Wall?

- Garbage Collection is a clear and dominant cause
- There seem to be practical heap size limits for applications with responsiveness requirements
- [Virtually] All current commercial JVMs will exhibit a multi-second pause on a normally utilized 2-4GB heap.
  - It's a question of "When" and "How often", not "If".
  - GC tuning only moves the "when" and the "how often" around
- Root cause: The link between scale and responsiveness
  - Without removing link, can't use >~$500 worth of 2011 H/W.
  - Problem/gap growing at Moore's law rate

# What quality of GC is responsible for the Application Memory Wall?

- It is NOT about overhead or efficiency:
  - CPU utilization, bottlenecks, memory consumption and utilization
- It is NOT about speed
  - Average speeds, 90%, 99% speeds, are all perfectly fine
- It is NOT about minor GC events (right now)
  - GC events in the 10s of msec are usually tolerable for most apps
- It is NOT about the frequency of very large pauses
- It is all about the worst observable pause behavior
  - People avoid building/deploying visibly broken systems

# GC Problems

# Framing the discussion: Garbage Collection at modern server scales

- Modern Servers have 100s of GB of memory
- Each modern x86 core (when actually used) produces garbage at a rate of ¼ - ½ GB/sec +
- That's many GB/sec of allocation in a server
- Monolithic stop-the-world operations are the cause of the current Application Memory Wall
  - Even if they are done "only a few times a day"

# The things that seem "hard" to do in GC

- Robust concurrent marking
  - References keep changing
  - Multi-pass marking is sensitive to mutation rate
  - Weak, Soft, Final references "hard" to deal with concurrently
- [Concurrent] Compaction...
  - It's not the moving of the objects...
  - It's the fixing of all those references that point to them
  - How do you deal with a mutator looking at a stale reference?
  - If you can't, then remapping is a [monolithic] STW operation
- Young Generation collection at scale
  - Young Generation collection is generally monolithic, Stop-The-World
  - Young generation pauses are only small because heaps are tiny
  - A 100GB heap will regularly have several GB of live young stuff...

# How can we break through the Application Memory Wall?

# We need to solve the right problems

- Focus on the causes of the Application Memory Wall
  - Scale is artificially limited by responsiveness
- Responsiveness must be unlinked from scale:
  - Heap size, Live Set size, Allocation rate, Mutation rate
  - 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)

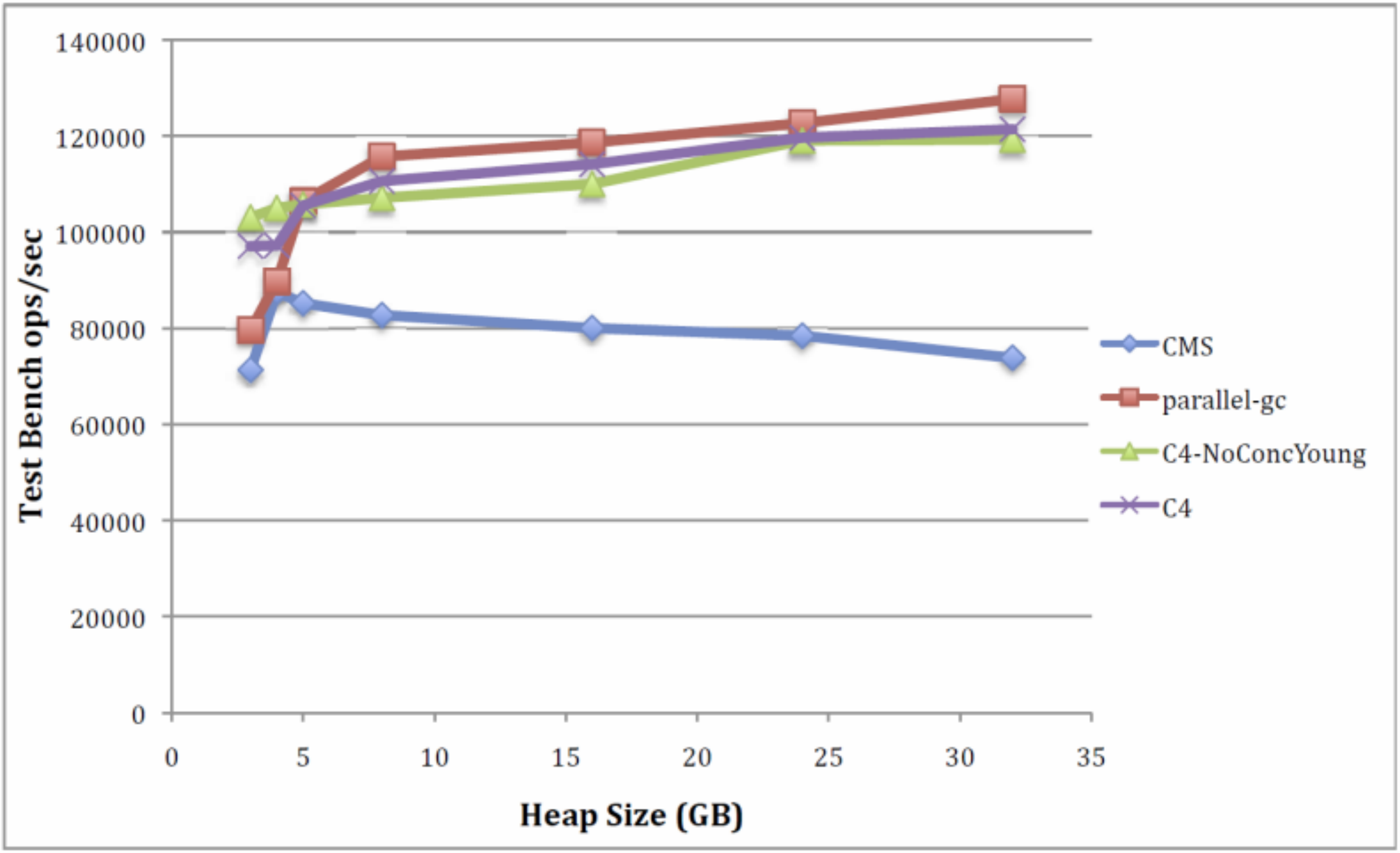
- Robust Concurrent Marking
  - In the presence of high mutation and allocation rates
  - Cover modern runtime semantics (e.g. weak refs)
- Compaction that is not monolithic-stop-the-world
  - Stay responsive while compacting ¼ TB heaps
  - Must be robust: not just a tactic to delay STW compaction
  - [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 be both be ok
  - Surprisingly little work done in this specific area

# Azul's "C4" Collector

## Continuously Concurrent Compacting Collector

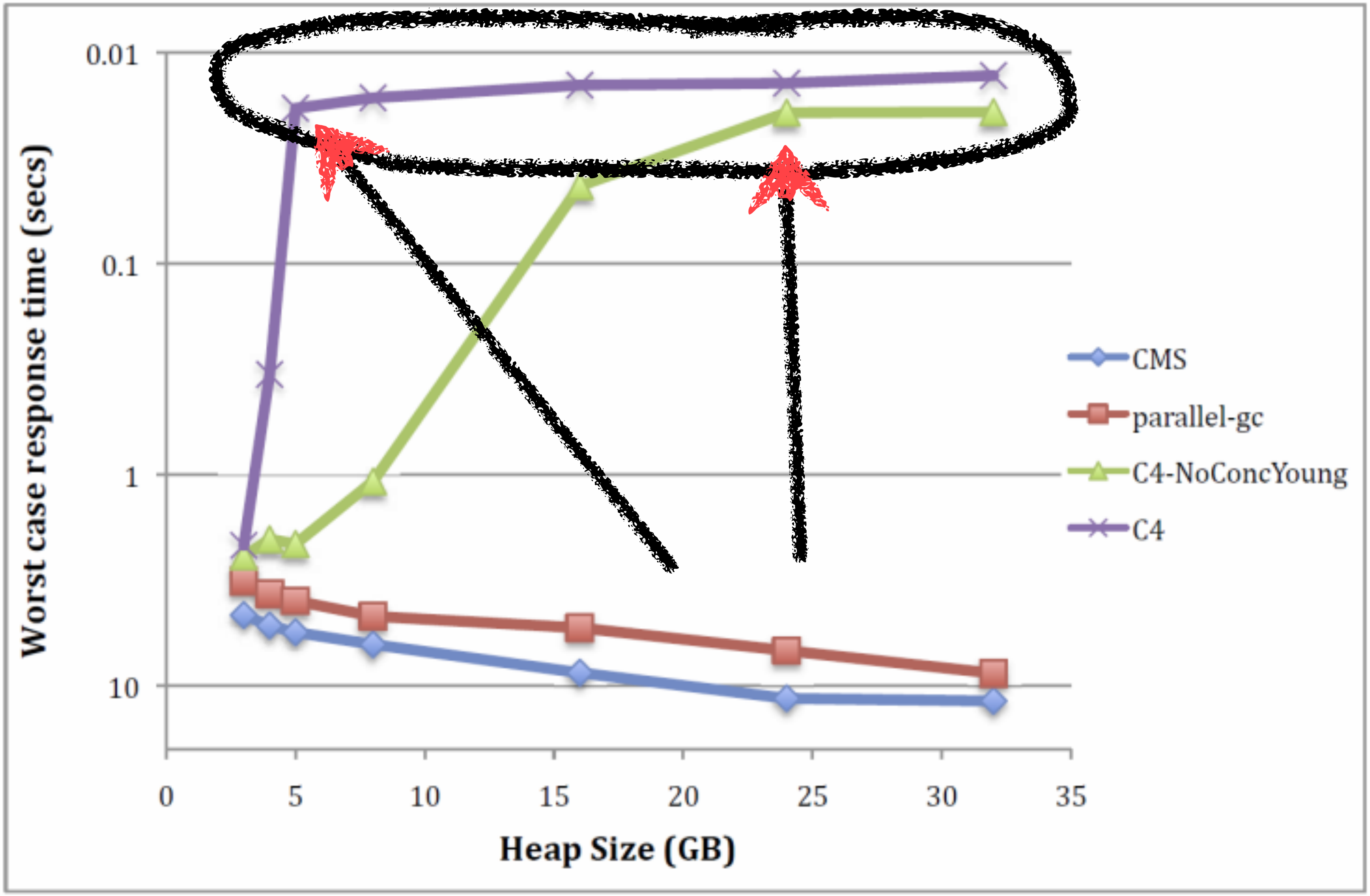
- Concurrent, compacting new generation
- Concurrent, compacting old generation
- Concurrent guaranteed-single-pass marker
  - Oblivious to mutation rate
  - Concurrent ref (weak, soft, final) processing
- Concurrent Compactor
  - Objects moved without stopping mutator
  - References remapped without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

# Sample throughput



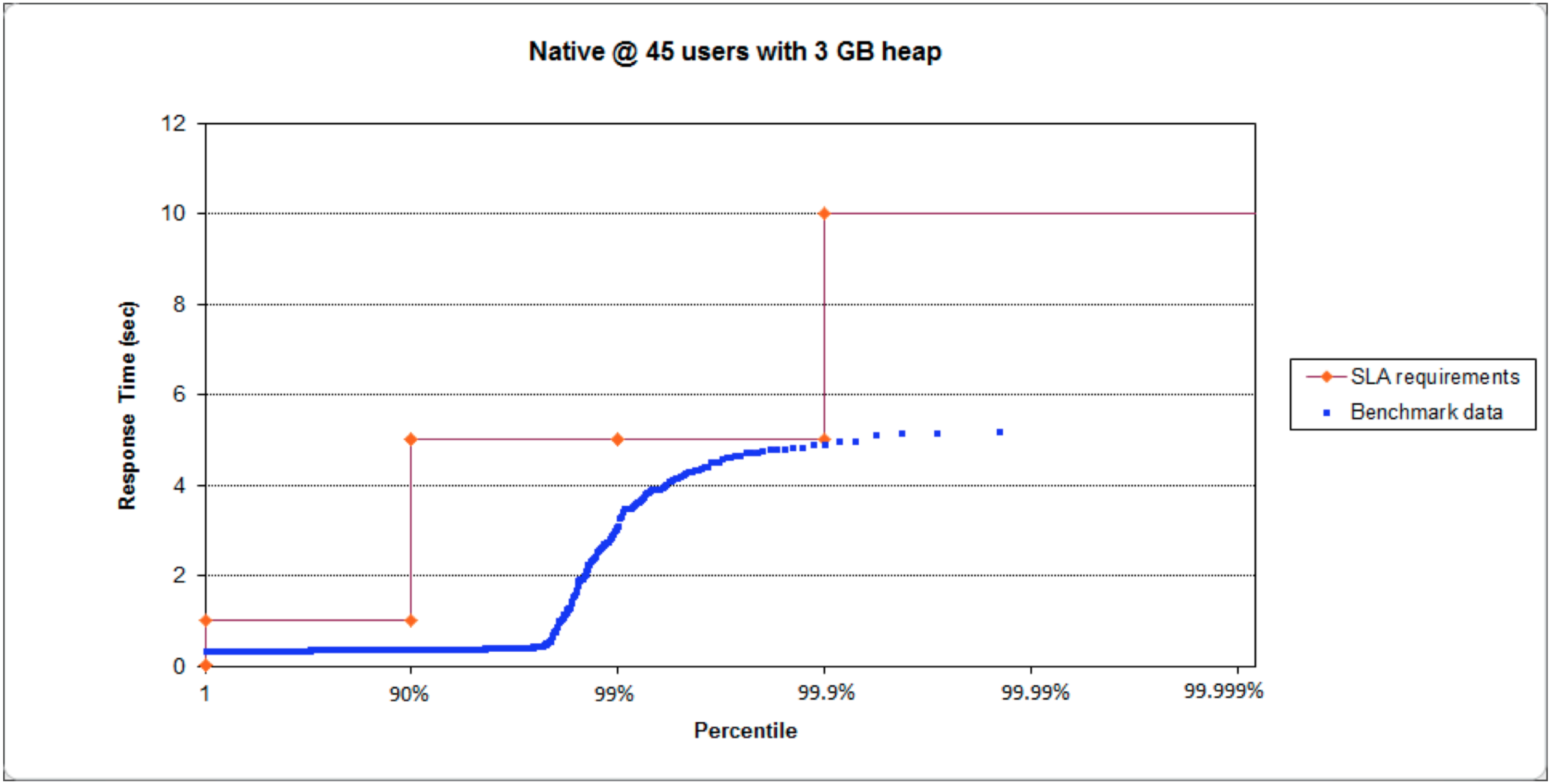

- SpecJBB + Slow churning 2GB LRU Cache
- Live set is ~2.5GB across all measurements
- Allocation rate is ~1.2GB/sec across all measurements

# Sample responsiveness improvement



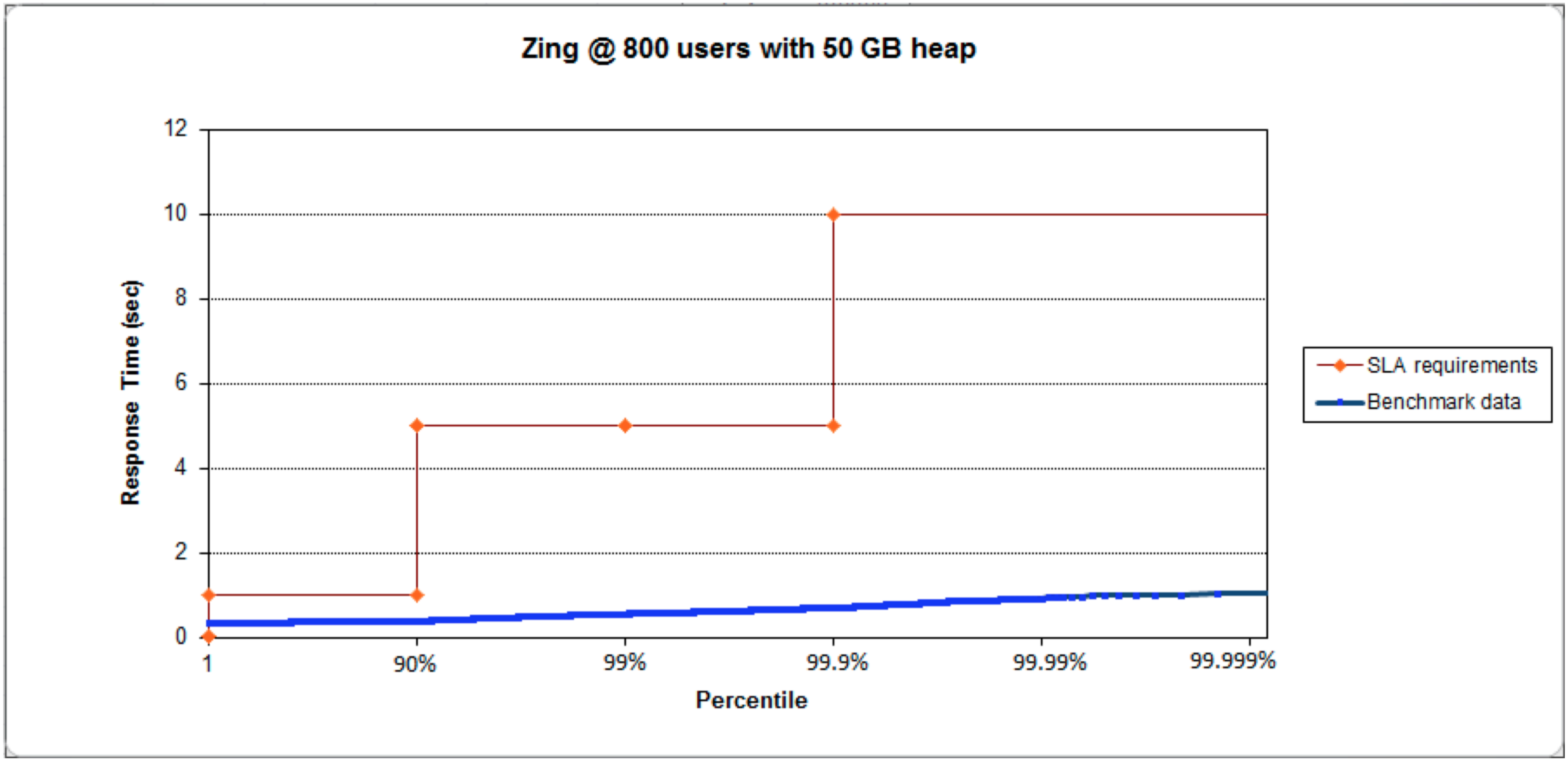

- SpecJBB + Slow churning 2GB LRU Cache
- Live set is ~2.5GB across all measurements
- Allocation rate is ~1.2GB/sec across all measurements

# Instance capacity test: "Fat Portal"
# CMS: Peaks at ~ 3GB / 45 concurrent users




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

# Instance capacity test: "Fat Portal"
# C4: still smooth @ 800 concurrent users

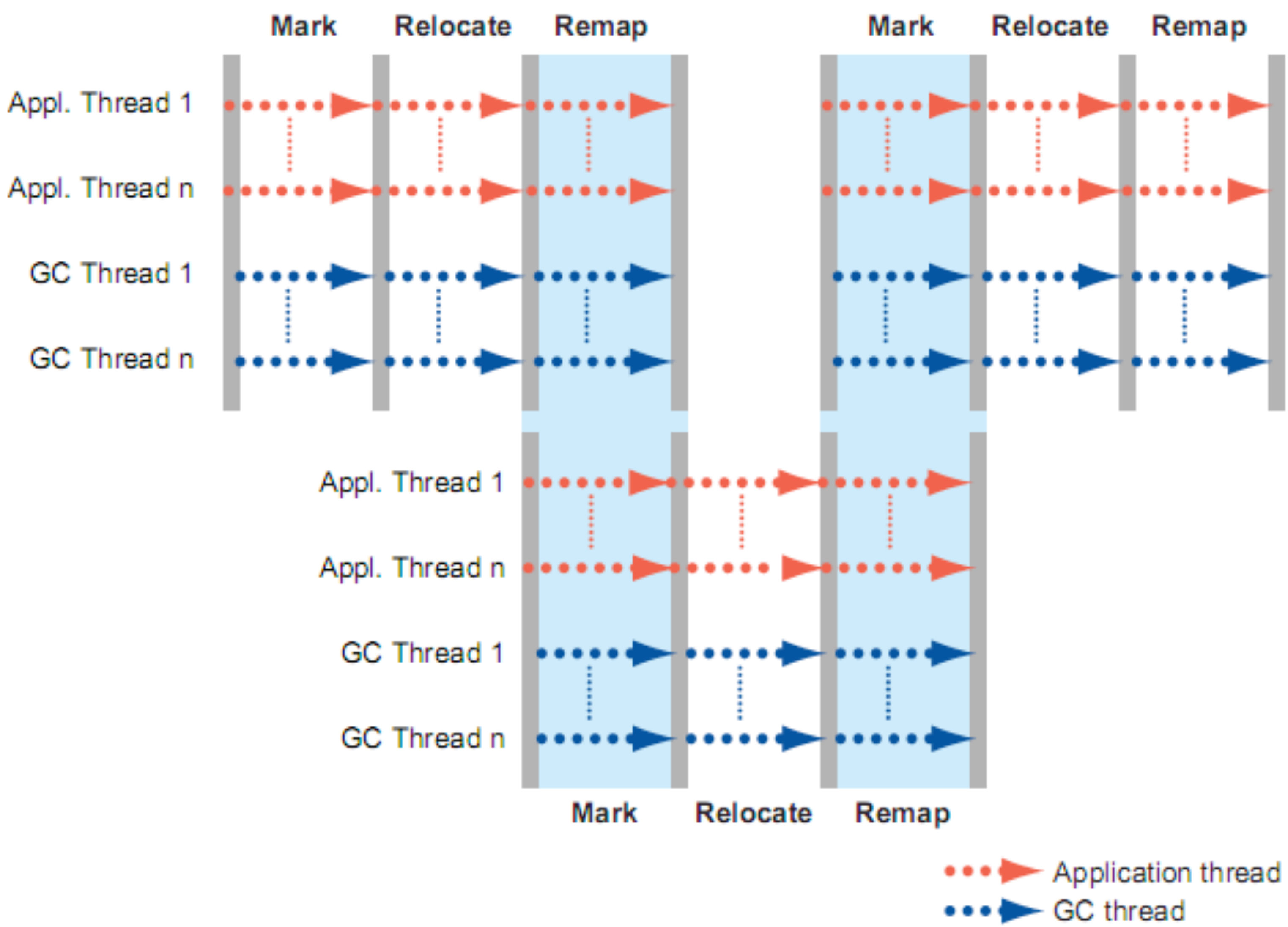


# C4 Algorithm fundamentals

# 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

# The C4 GC Cycle



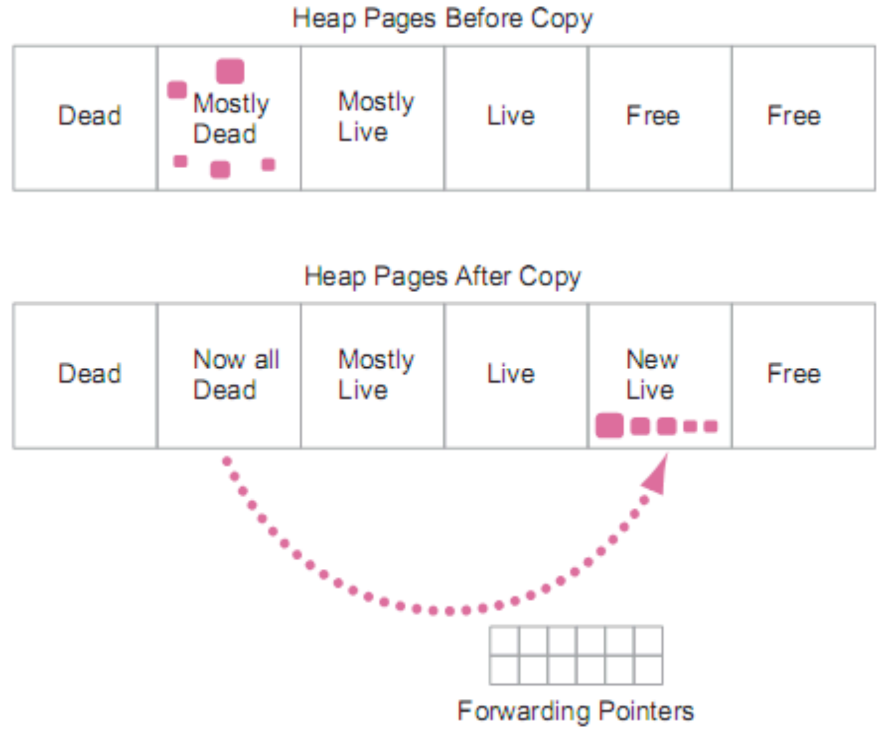
# Mark Phase

- Mark phase finds all live objects in the Java heap
- Concurrent, predictable: always complete in a single pass
- Uses LVB to defeat concurrent marking races
  - Tracks object references that have been traversed by using an "NMT" (not marked through) metadata state in each object reference
  - Any access to a not-yet-traversed reference will trigger the LVB
  - Triggered references are queued on collector work lists, and reference NMT state is corrected
  - "Self healing" corrects the memory location that the reference was loaded from
- Marker tracks total live memory in each memory page
  - Compaction uses this information to go after the sparse pages first

(But each cycle will tend to compact the entire heap...)

# Relocate Phase

- Compacts to reclaim heap space occupied by dead objects in "from" pages without stopping mutator
- Protects "from" pages.
- Uses LVB to support concurrent relocation and lazy remapping by triggering on any access to references to "from" pages
- Relocates any live objects to newly allocated "to" pages
- Maintains forwarding pointers outside of "from" pages
- Virtual "from" space cannot be recycled until all references to relocated objects are remapped

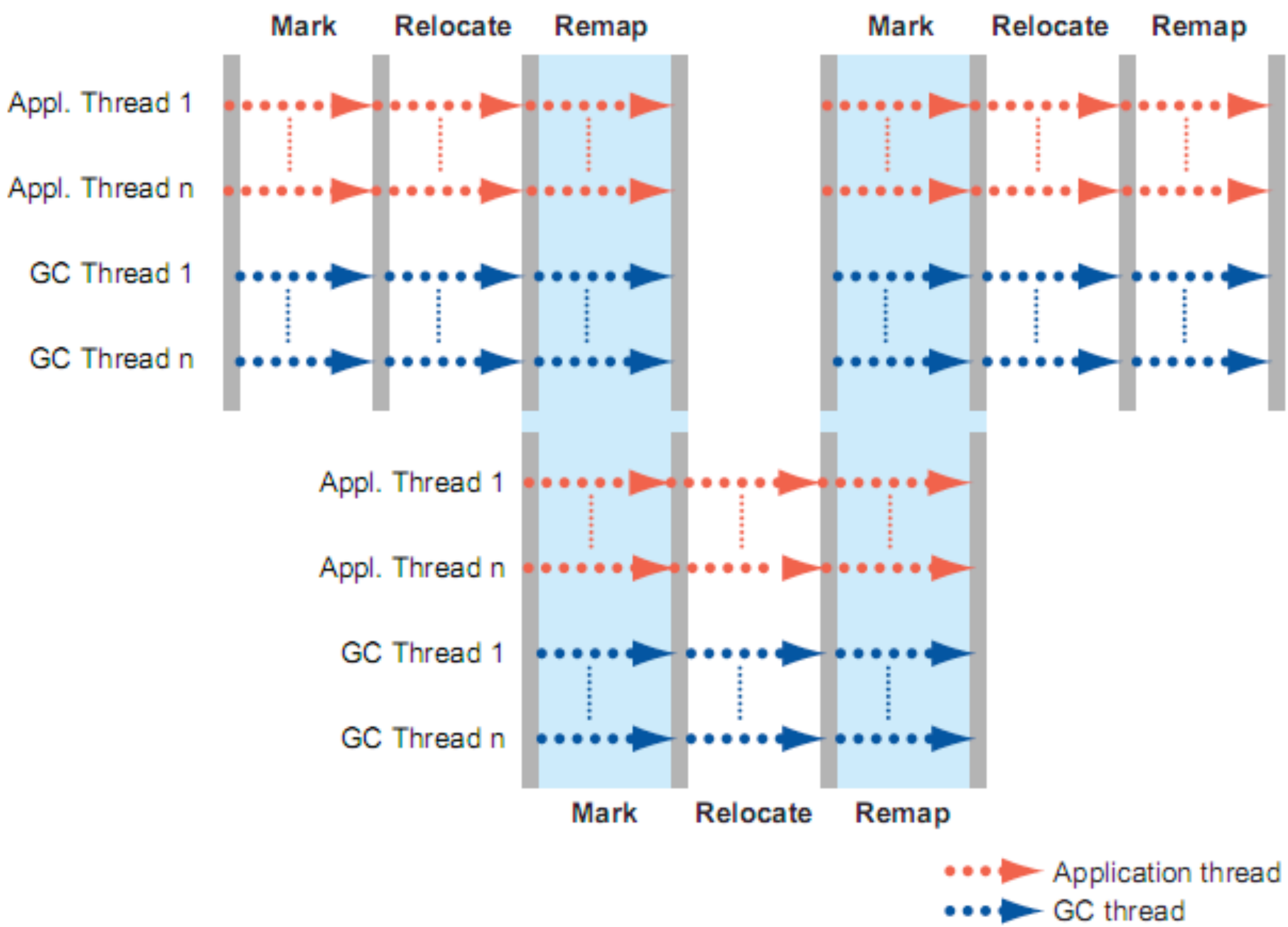



- "Quick Release": Physical memory can be immediately reclaimed, and used to feed further compaction or allocation

# Remap Phase

- Scans all live objects in the heap
- Looks for references to previously relocated objects, and updates ("remaps") them to point to the new object locations
- Uses LVB to support lazy remapping
  - Any access to a not-yet-remapped reference will trigger the LVB
  - Triggered references are corrected to point to the object's new location by consulting forwarding pointers
  - "Self healing" corrects the memory location the reference was loaded from
- Overlaps with the next mark phase's live object scan
  - Mark & Remap are executed as a single pass

# The C4 GC Cycle



# 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 …
```

# The complete guide to Zing GC tuning

java -Xmx40g

# Q & A

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.