GC Nirvana

High throughput, low latency, and lots of state, all at the same time

Gil Tene, CTO & Co-Founder

Azul systems

About the speaker

Gil Tene (CTO), Azul Systems

- At Azul, we deal with concurrent GC on a daily basis
- Azul makes Java scalable thru virtualization
  - We make physical (Vega™) and Virtual (Zing™) appliances
  - Our appliances power JVMs on Linux, Solaris, AIX, HPUX, …
  - Production installations ranging from 1GB to 300GB+ of heap
  - Zing VM instances smoothly scale to 100s of GB, 10s of cores
- Concurrent GC has always been a must in our space
  - It's now a must in everyone's space - can't scale without it
- Focused on concurrent GC for the past 8 years
  - Azul's GPGC designed for robustness, low sensitivity

Azul Systems

Java For a Virtualized World

- Founded in 2002, Zing is Azul's 4th generation product
- Privately held with offices around the globe
- Numerous industry firsts:
  - Segmented JVM, pauseless GC, Elastic memory
- Proven, mission-critical deployments in >70 global 2000 accounts
- Recognized innovator with award-winning technology
  - 28 patents issued, 23 pending

The GC Trifecta – Latency, Throughput, Size

- Latency
  - The collector's effect on application response times
- Throughput
  - The collector's ability to collect and traverse data
  - The collector's ability to keep up with application throughput
    - Allocation rate
    - Mutation rate
    - Fragmentation & fragmentation rate
- Data Set Size
  - The collector's ability to handle an application's data set

Application memory

Memory.

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

Why ~2-4GB?
It's all about GC (and only GC)

- Seems to be the practical limit for responsive applications
- A 100GB heap won't crash. It just periodically "pauses" for many minutes at a time.
- [Virtually] All current commercial JVMs will exhibit a periodic multi-second pause on a normally utilized 2-4GB heap.
  - It's a question of "When", not "If".
  - GC Tuning only moves the "when" and the "how often" around
- "*Compaction is done with the application paused. However, it is a necessary evil, because without it, the heap will be useless…*" (JRockit RT tuning guide).

Maybe 2-4GB is simply enough?

- We hope not (or we'll all have to look for new jobs soon)
- Plenty of evidence to support pent up need for more heap
- Common use of lateral scale across machines
- Common use of "lateral scale" within machines
- Use of "external" memory with growing data sets
  - Databases certainly keep growing
  - External data caches (memcache, JCache, JavaSpaces)
- Continuous work on the never ending distribution problem
  - More and more reinvention of NUMA
  - Bring data to compute, bring compute to data

How much memory do applications need?

- “640K ought to be enough for anybody”

WRONG! So what’s the right number?

- 6,400K? (6.4MB)?
- 64,000K? (64MB)?
- 640,000K? (640MB)?
- 6,400,000K? (6.4GB)?
- 64,000,000K? (64GB)?

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

"Tiny" application history

Moore's Law:
transistor counts grow

- ~2x every 18 months
- ~100x every 10 yrs

Zing VM

2010 — 100GB apps on 256 GB

Java

2000 — 1GB apps on a 2 – 4 GB server

1990 — 10MB apps on a 32 – 64 MB server

1980 — 100KB apps on a ¼ to ½ MB Server

The ~~640K~~ Memory problem

Scale is now entirely limited by Garbage Collection

- Java runtimes “misbehave” above ~2-3GB of memory
  - Most people won’t tolerate 20 second pauses
- It takes 50-100 JVM instances to fill up a 96-256GB server
  - This is getting embarrassing…
- The problem is in the software stack
  - Artificial constraints on memory per instance
  - GC Pause time is the only limiting factor for instance size
  - Can’t just “tune it away”
- ***Solve*** GC, and you’ve solved the problem
- Azul has **solved** GC, uncapping runtime scalability
  - Proven GC solution now available on virtualized x86

Some Terminology

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

Terminology

Useful terms for discussing concurrent collection

- Mutator
  - Your program…
- Parallel
  - Can use multiple CPUs
- Concurrent
  - Runs concurrently with program
- Pause time
  - Time during which mutator is not running any code
- 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

Metrics

Useful metrics for discussing concurrent 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

The "hard" things to do in GC

- Robust concurrent marking
  - Refs keep changing
  - Multi-pass marking sensitive to mutation rate
  - Weak, Soft, Final refs "hard" to deal with concurrently
- [Concurrent] Compaction…
  - Its not the moving of the objects…
  - It's the fixing of all those refs that point to them
  - How do you deal with a mutator looking at a stale ref?
  - If you can't, then remapping is a STW operation

- Without solving Compaction, GC won't be solved.

Can’t ignore “bad” GC Compaction? What Compaction?

HotSpot CMS

Collector mechanism classification

- Stop-the-world compacting new gen (ParNew)
- Mostly Concurrent, non-compacting old gen (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 (Stop the world).
  - Used for Compaction, etc.

Azul GPGC

Collector mechanism classification

- 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
  - Can relocate entire generation in every GC cycle
- No Stop-the-world fallback
  - Always compacts, and does so concurrently

Problems, Solutions

Garbage Collection & Compaction

- Compaction is inevitable
  - Moving anything requires scanning/fixing all references
  - Usually the worst possible thing that can happen in GC
- You can delay compaction, but not get rid of it
- Delay tactics focus on getting "easy empty space" first
- Most objects die young
  - 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
  - So track dead space in lists, and reuse it in place
  - But eventually, space gets fragmented, and needs to be moved
- Eventually, *all* collectors compact the heap

Problem: Garbage Collection Reality

- Responsiveness:
  - Compaction is inevitable
  - Existing Java runtimes perform compaction as stop-the-world
  - Delay games are the only current tuning strategy
  - The inevitable pause times are linear to memory heap sizes
- Scale:
  - Responsiveness requirements limit heap sizes
  - Limited heap sizes limit scale, sustainable throughput
  - CPU core use limited by heap
  - Throughput, Latency, and Scale all fighting each other
- Complexity:
  - Instance sprawl is the ONLY way to add or use capacity
  - 2010: It takes ~50 2GB JVMs to fill up a $7K server….

Solution: The Zing Garbage Collector

- Concurrent compaction, not stop-the-world
- Robust. Collector is insensitive to:
  - Heap size, allocation rate, mutation rate, weak/soft reference use, …
- Runtime responsiveness is now independent of:
  - Data set size, throughput, concurrent sessions, …
- Predictable, wide operating range
  - No need for fine-tuning. No need for delay games.
  - No “rare” bad events
  - WYTIWYG - What you test is what you get
- Simplicity
  - Individual instances can now easily scale within available resource
  - No more building 100-way distributed networks *within* a server

So, How do we do it?

Zing GPGC – a taste of the secret sauce

- We live and die by our Loaded Value Barrier (LVB)
  - Every Java ref is verified as “sane” when loaded
  - “non-sane” refs are fixed in a self-healing barrier
- Refs that have not yet been “marked through” are caught
  - Guaranteed single pass marker
- Refs that point to relocated objects are caught
  - Lazily [and concurrently] remap refs, no hurry
  - Relocation and remapping are both concurrent
- We use “quick release” to recycle memory
  - Forwarding information is kept outside of object pages
  - Immediately upon relocation, we release physical memory
  - “Hand-over-hand” compaction without requiring empty memory
- We use new virtual memory ops in a new kernel…

Problem: Memory Management and Garbage Collection

- GC is core to most Java Runtime limitations
  - Responsiveness, Heap Size, Throughput, Scale
  - Stop the world compaction grows with size
- GC solutions limited by OS environment
  - Concurrent compaction is practical with proven algorithms
  - e.g. Azul's GPGC, which has a 5 year production track record
  - But proven algorithms rely on missing OS features
  - Need sustained remappings at rates 100s of GB/sec
  - Peak remap commit in the 10s of TB/sec
- Slow, high-overhead memory management semantics
  - OS virtual memory semantics include much unneeded cost
  - Small pages, costly remapping, TLB invalidates, per page costs
  - No interfaces to allow Runtime to control looser semantics
  - Sustainable and peak remap rates are below 1GB/sec

Solution: GC-optimized Memory Mgmt

- Zing Virtual Appliance
  - Transparently executes Java Runtime launched from external OS
  - GC-optimized OS kernel
  - Supports new memory management semantics
- GC-optimized virtual memory support
  - Loose large page TLB invalidates under explicit runtime control
  - Batched, shadow operations with bulk commits
  - Sustainable Remap rates of several TB/sec (>1,000x faster)
  - Remap Commit Rates of 100s of TB/sec (>1,000,000x faster)
  - The difference between a 20 second pause and 20usec phase shift
- GC-optimized physical memory support
  - Process local free lists allow for safe TLB-invalidate & zero bypass
  - Tightly accounted, predictable, performant

Java & Virtualization

- How many of you use virtualization?
  i.e. VMWare, KVM, Xen, desktop virtualization (Fusion, Parallels, VirtualBox, etc.)

- How many of you use it for production applications?

- How many of you think that virtualization will make your application run faster?

The Virtualization Tax

- Virtualization is universally considered a “tax”
- The Focus is on measuring and reducing overhead
- Everyone hopes to get to
  “virtually the same as non-virtualized”
- Plenty of infrastructure benefits
- But what are the application benefits?

Problem:
Java Runtimes are already limited

Common Java Runtime Limitations

- Responsiveness
- Scale and complexity
- Rigid, non-elastic, and inefficient
- Sensitivity to load, fragility
- Poor production-time visibility

These are “pre-existing conditions”

Problem:
Virtualization only makes things worse …

- Moving to virtualized environments:
  - Nobody expects applications to run faster or better
  - Best hope is that virtualization "won't hurt too much"
- Common published virtualization best practices for Java:
  - Use one JVM process per Guest OS
  - Use the fewest cores you can get away with
  - Turn off ballooning, partition memory, avoid elasticity
- Tier-1 and some Tier-2 applications avoid virtualization
  - No ***Application*** benefits expected
  - Application behavior considered more important than virtualization benefits to infrastructure

What if……

- What if we could do better?
- What if virtualization actually made applications better?
- What if virtualization was the way to solve the pre-existing Java limitations?

The Zing Platform: Virtualization with ***Application*** Benefits

If you want to:…

- ***Improve*** response times:
- ***Increase*** Transaction rates:
- ***Increase*** Concurrent users:
- ***Forget*** about GC pauses:
- Eliminate daily restarts:
- Elastically grow during peaks:
- Elastically shrink when idle:
- Gain production visibility:

Zing™ Platform

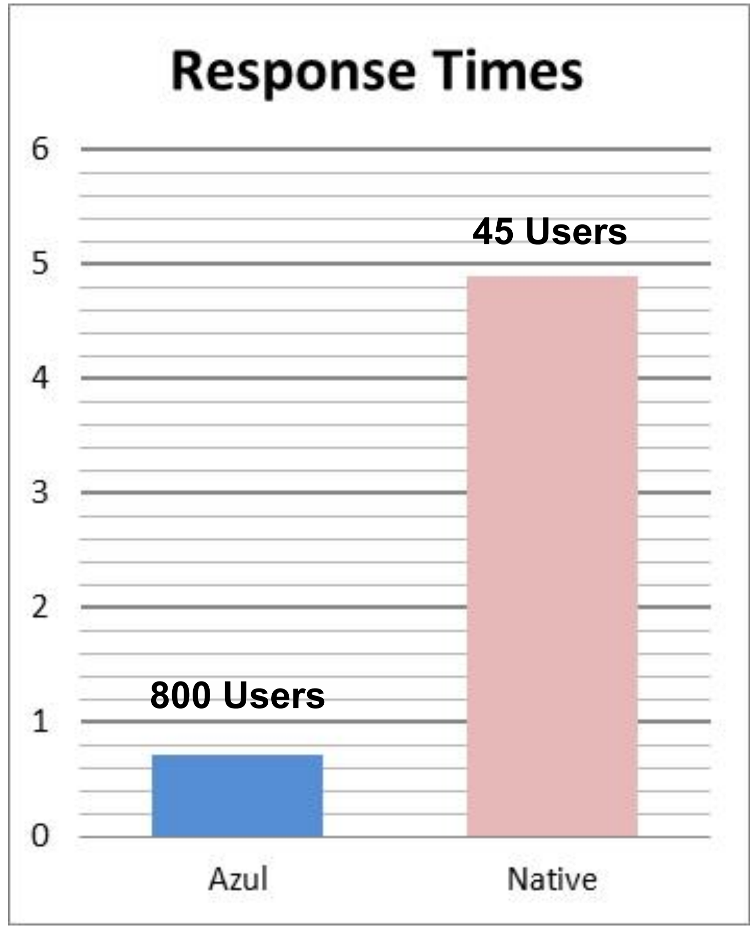
On virtualized

commodity H/W

Head to Head comparison

Same hardware, same application

- >17x more concurrent users
- >6x better response times



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

Head to Head comparison

Same hardware, same application

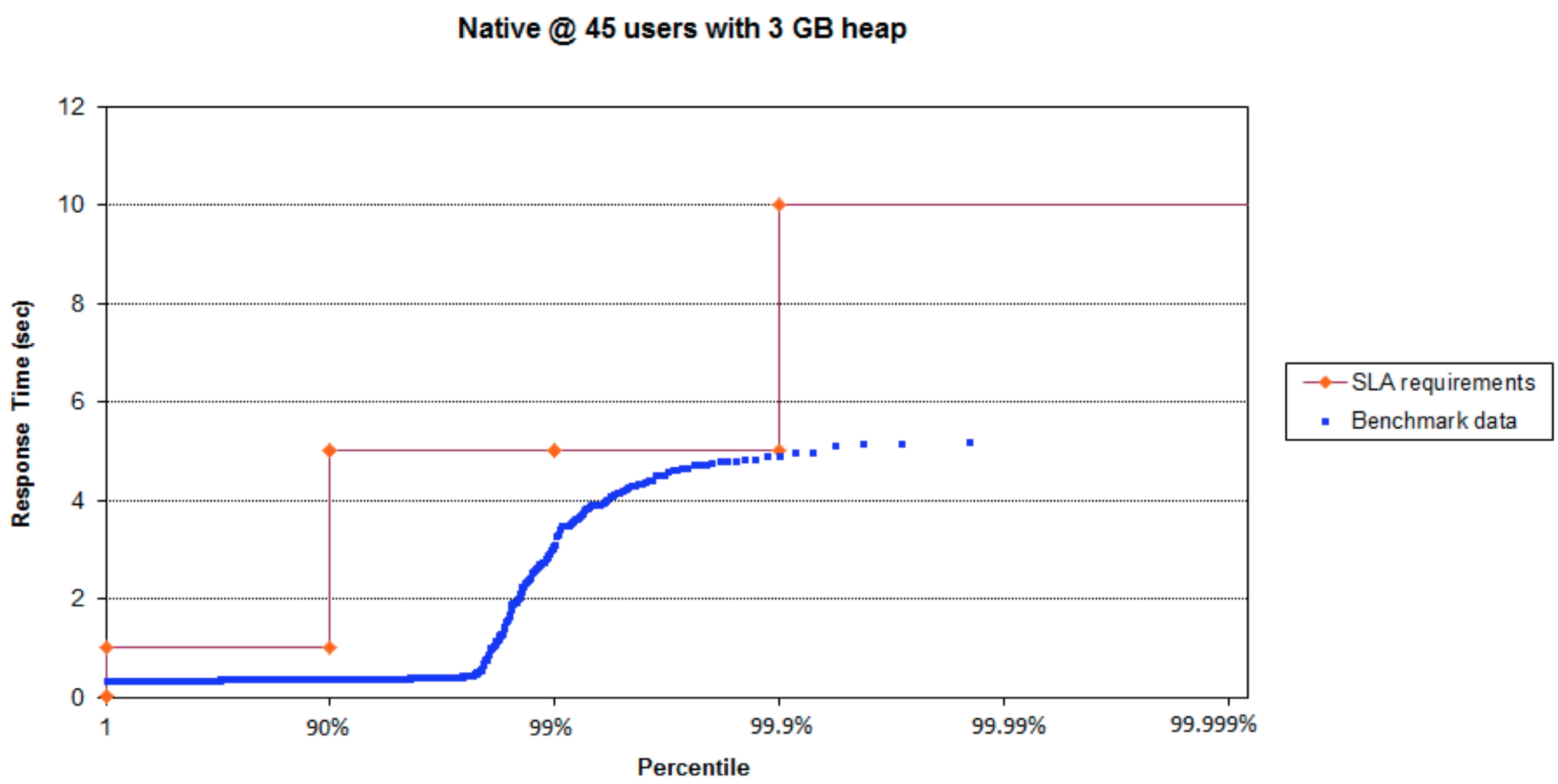
- LifeRay Portal on JBoss
- Simple client load
  - ~10 sec. think times
  - ~40 MB temporary data generated per ~300ms transaction
  - ~20 MB session state
  - very slow churning LRU-like background load (@<20MB/sec)
- Sustainable SLA requirement:
  - Worst case < 10 sec.
  - 99.9% < 5 sec.
  - 90% < 1 sec.
  - Pushing pauses out of test window run not allowed.

Head to Head comparison

Same hardware, same application

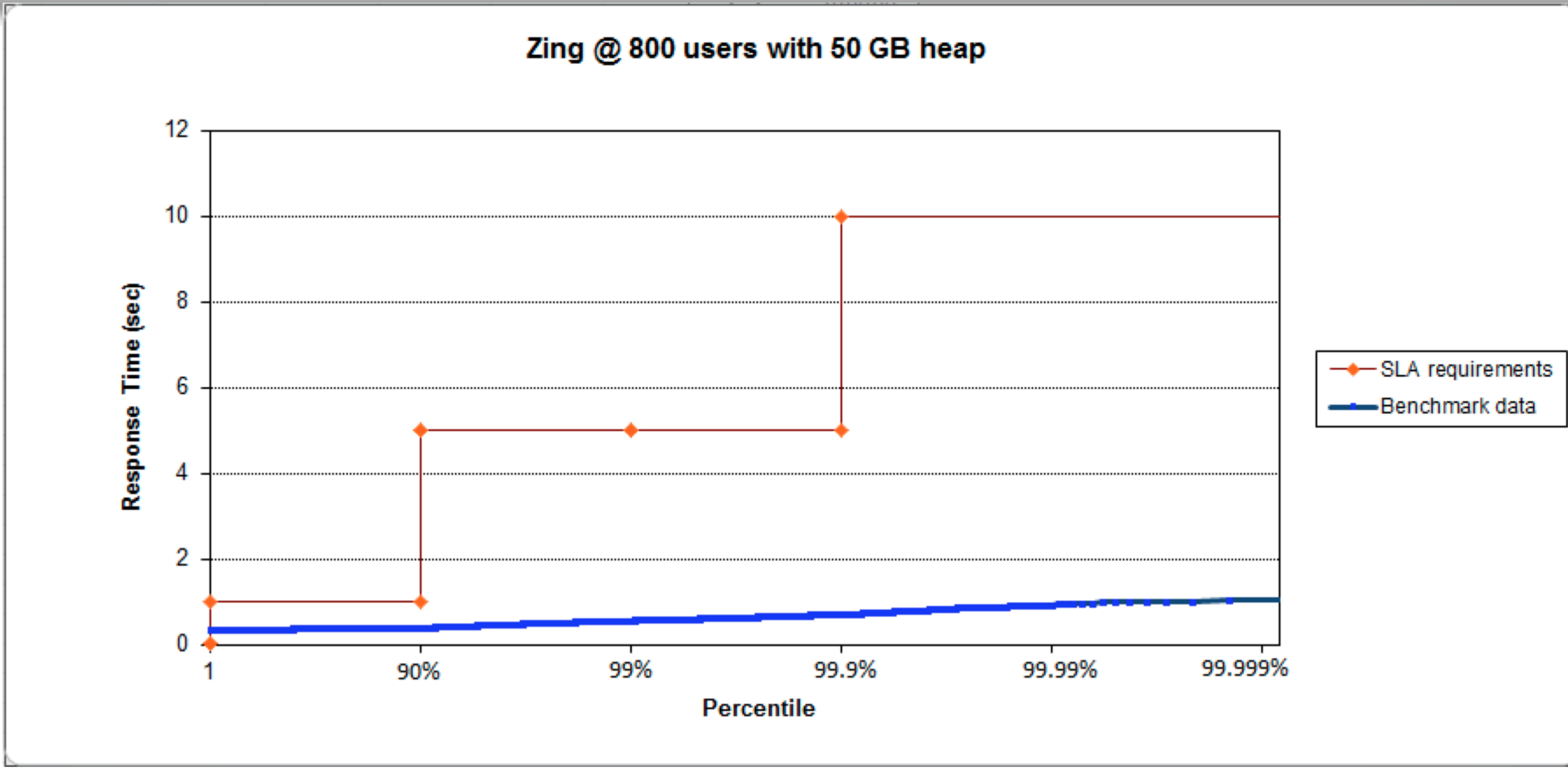
- Hardware
  - 2x Intel Xeon 5620 (12 cores), 96GB
  - ~$6,700 as of Oct. 2010… (~$1.75/GB/month)
- “Native” (aka “non-Virtualized”):
  - Fedora Core 12
  - Native HotSpot JVM
- Virtualized:
  - VMWare ESX 4.0
  - Zing Virtual Appliance
  - Fedora Core 12 (running as VMWare guest)
  - Zing JVM

Native JVM: Peaks at 45 concurrent users



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

Zing JVM: smooth @ 800 concurrent users



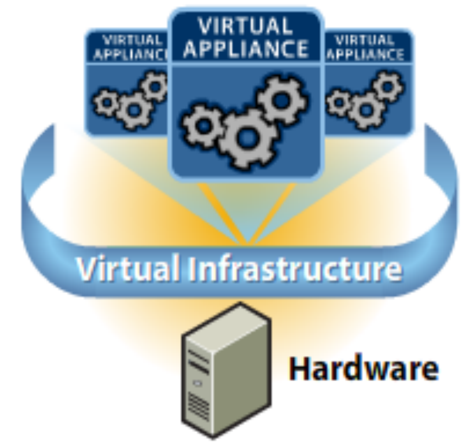
How to deliver a better runtime

- Java Runtimes are limited on existing platforms
  - Modern H/W is far more scalable than the runtimes are
- OS environment limitations are in the way
  - lack features to support pauseless GC, elasticity, etc.
- A better runtime needs a better place to run…
  - However, applications are strongly invested in OSs…
- So, how can we deliver:
  - A better runtime
  - A better place to run
  - All without changing the OS, or the application
- The Answer: Java Runtime Virtualization

Zing Platform Components

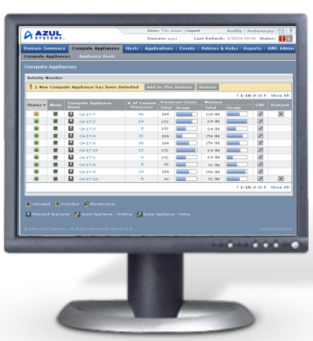
Zing Java Virtual Machine

Virtualized Java Runtime



Zing Java Virtual Appliance

Java-Optimized Execution Environment



Zing Resource Controller

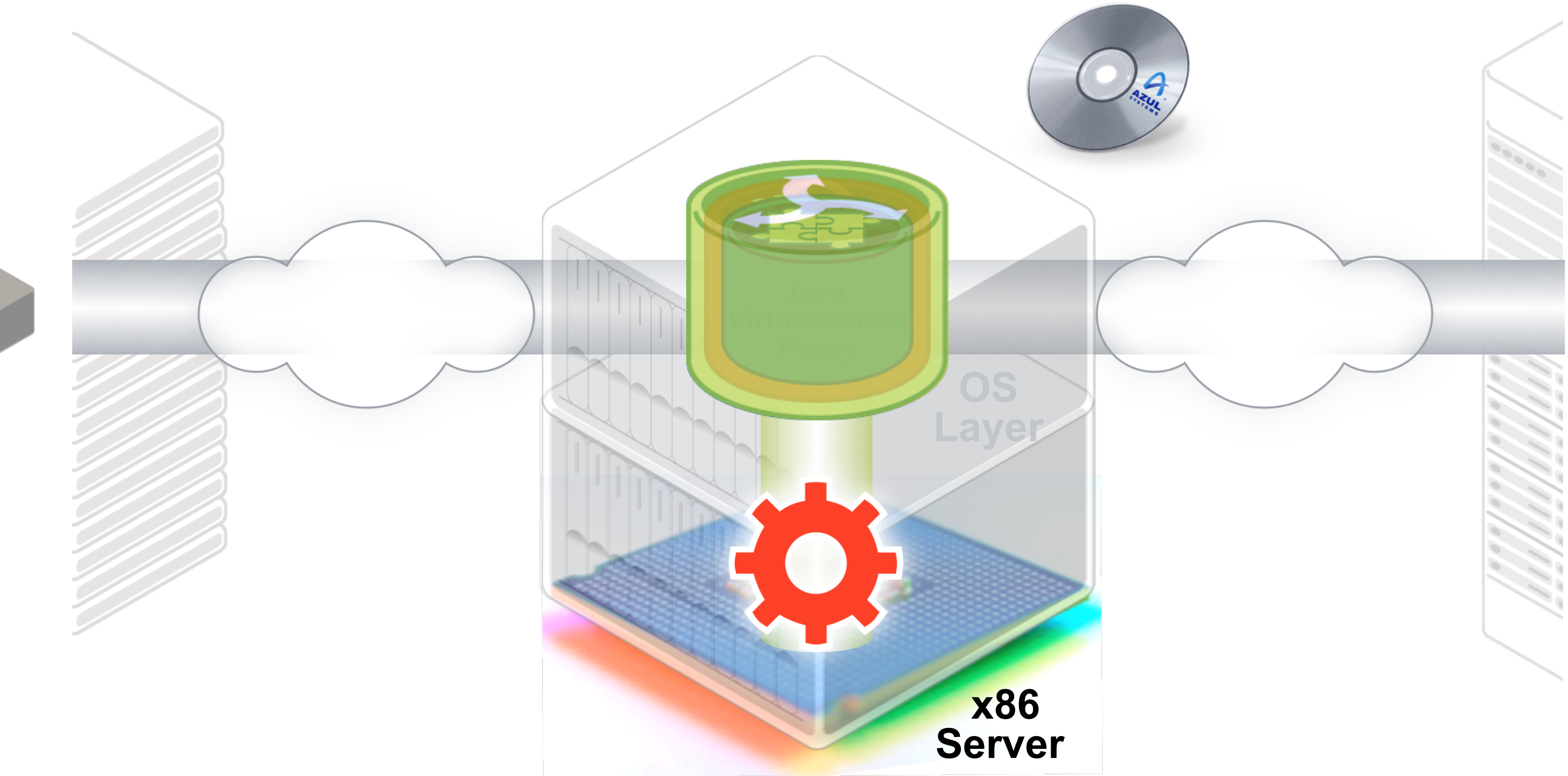
Centralized Monitoring & Mgmt

Zing Vision

Non-intrusive Visibility

Zing - Java Runtime Virtualization

Liberating Java From the limitations of the OS



The Better Runtime: Zing JVM

- **Completely** solves the GC pause/instability problem…
- Can make full use of modern hardware capacities
- Smooth, wide operating range
  - Consistent response time
  - Insensitive to data size, concurrent sessions, throughput, …
  - Works well between 1GB and 1TB, 1 core and tens of cores
- Elastic footprint
  - Grows and shrinks memory footprint as needed
  - Can use shared 'Insurance' memory to survive peaks & leaks
  - Can use shared 'Performance" memory to keep up with loads
  - No need to get sizing exactly right, saves tuning time
- Production-time visibility
  - Zero-overhead, deep drill-down detail on threads, memory, etc.

The Better Place to Run: Zing Virtual Appliance

- Transparently powers Zing JVMs on a variety of OSs
  - Linux, Solaris (both SPARC & x86), Windows, AIX, HP/UX z/Linux…
- Optimized Environment for running Java Runtimes
- A turnkey VM image, deployable on VMWare and KVM
- Supports key features behind:
  - Java Virtualization
  - Pauseless GC
  - Smooth operating range
  - Elastic Memory
  - Zero-overhead visibility
- Controlled and managed by Zing Resource Controller

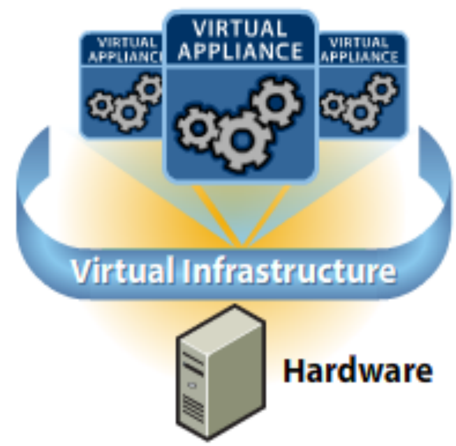
Zing Platform Components

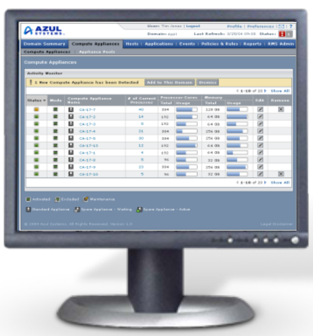
Zing Java Virtual Machine

Virtualized Java Runtime

Zing Java Virtual Appliance

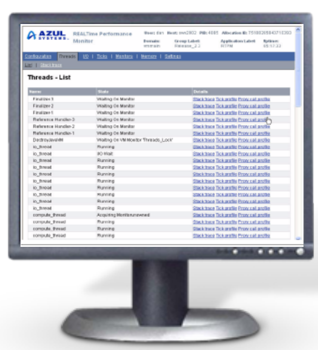
Java-Optimized Execution Environment





Zing Resource Controller

Centralized Monitoring & Mgmt



Zing Vision

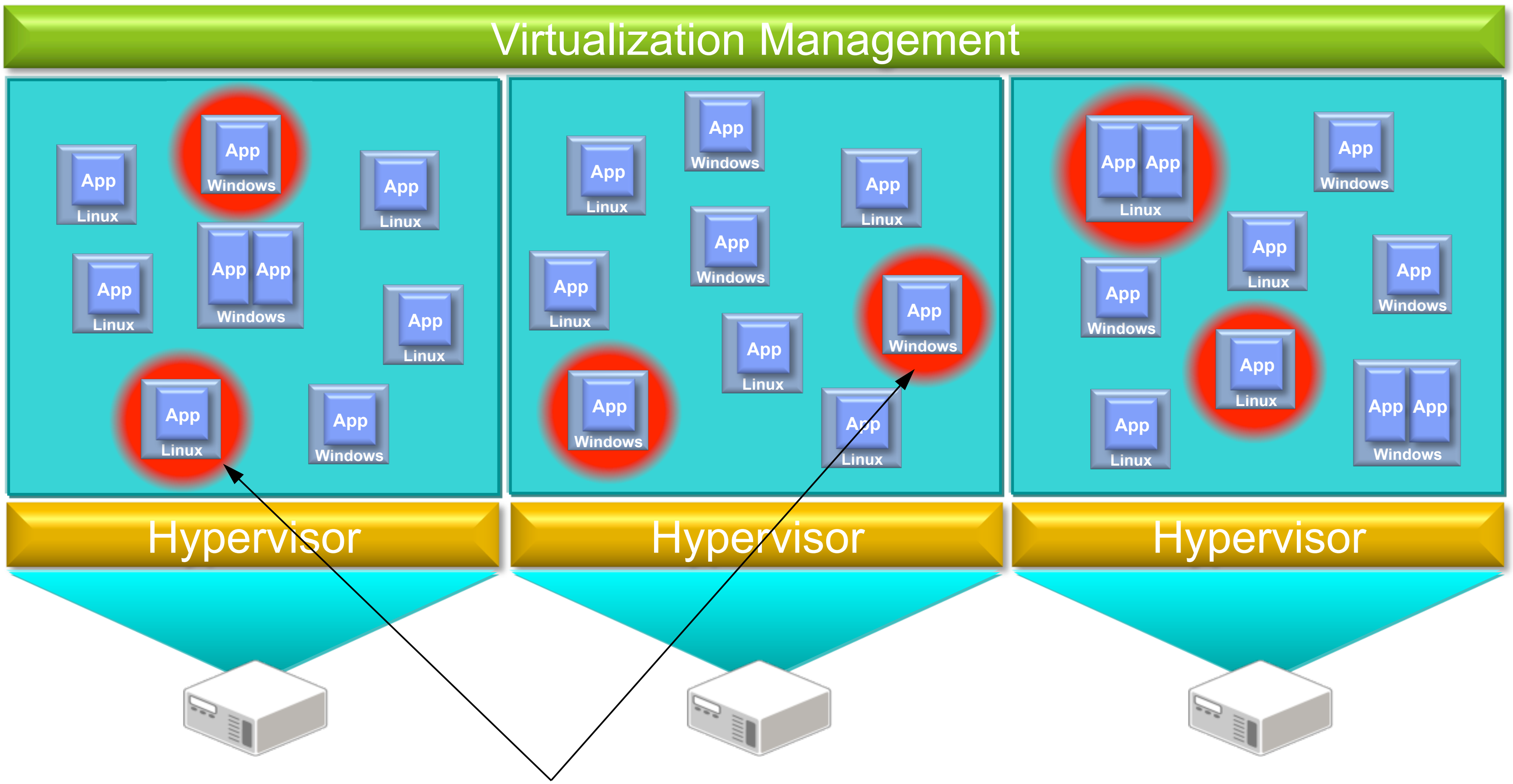
Non-intrusive Visibility

Q & A

Gil Tene
CTO, Azul Systems

Current Virtualized Java Deployments

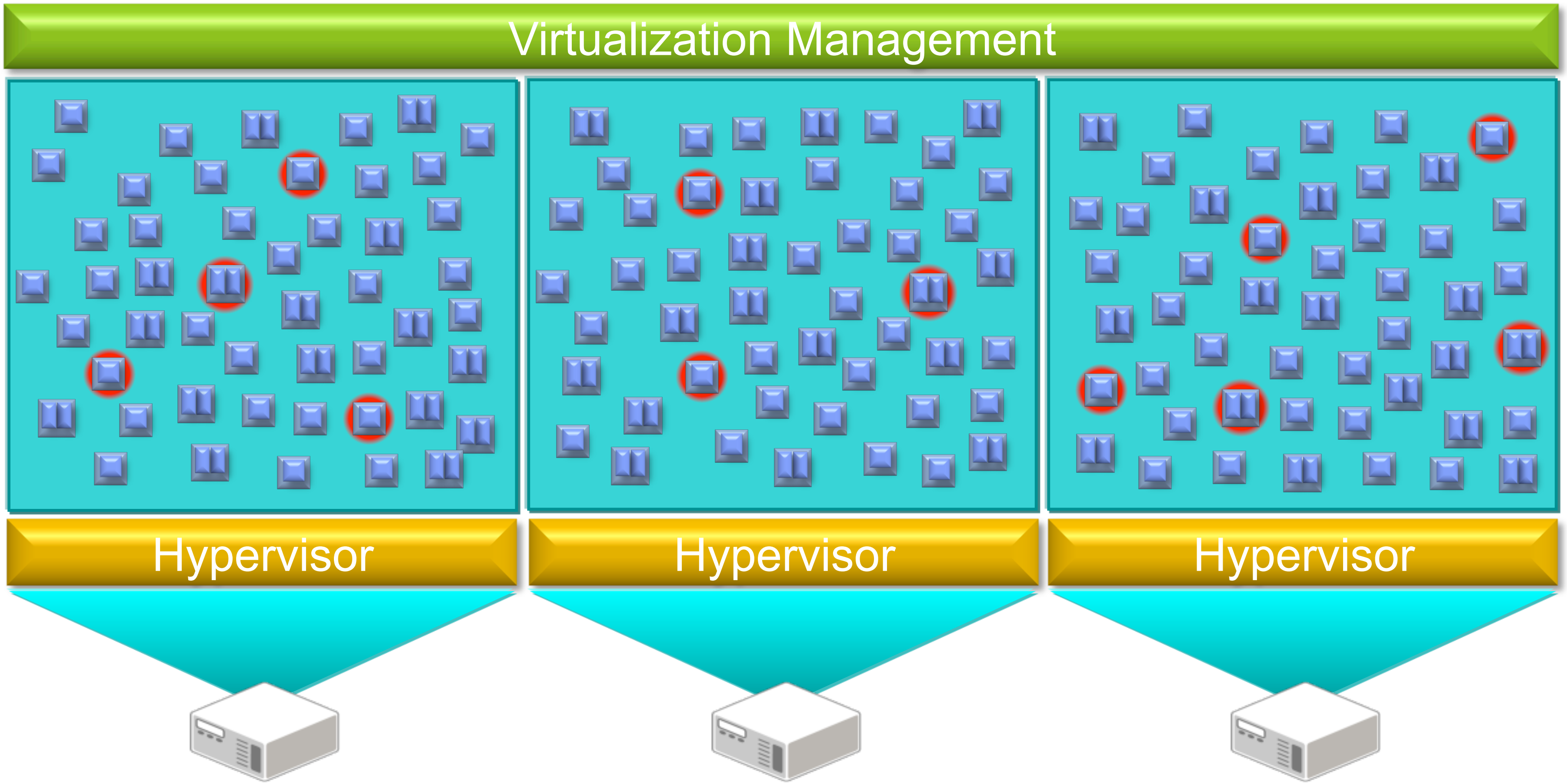
Limited scalability, many instances to manage, Inefficient use of resources



Today's JVMs are each limited to ~3-4 GBytes of memory before response times become unacceptable, ***limiting application instance scalability, throughput & resiliency***

Current Virtualized Java Deployments

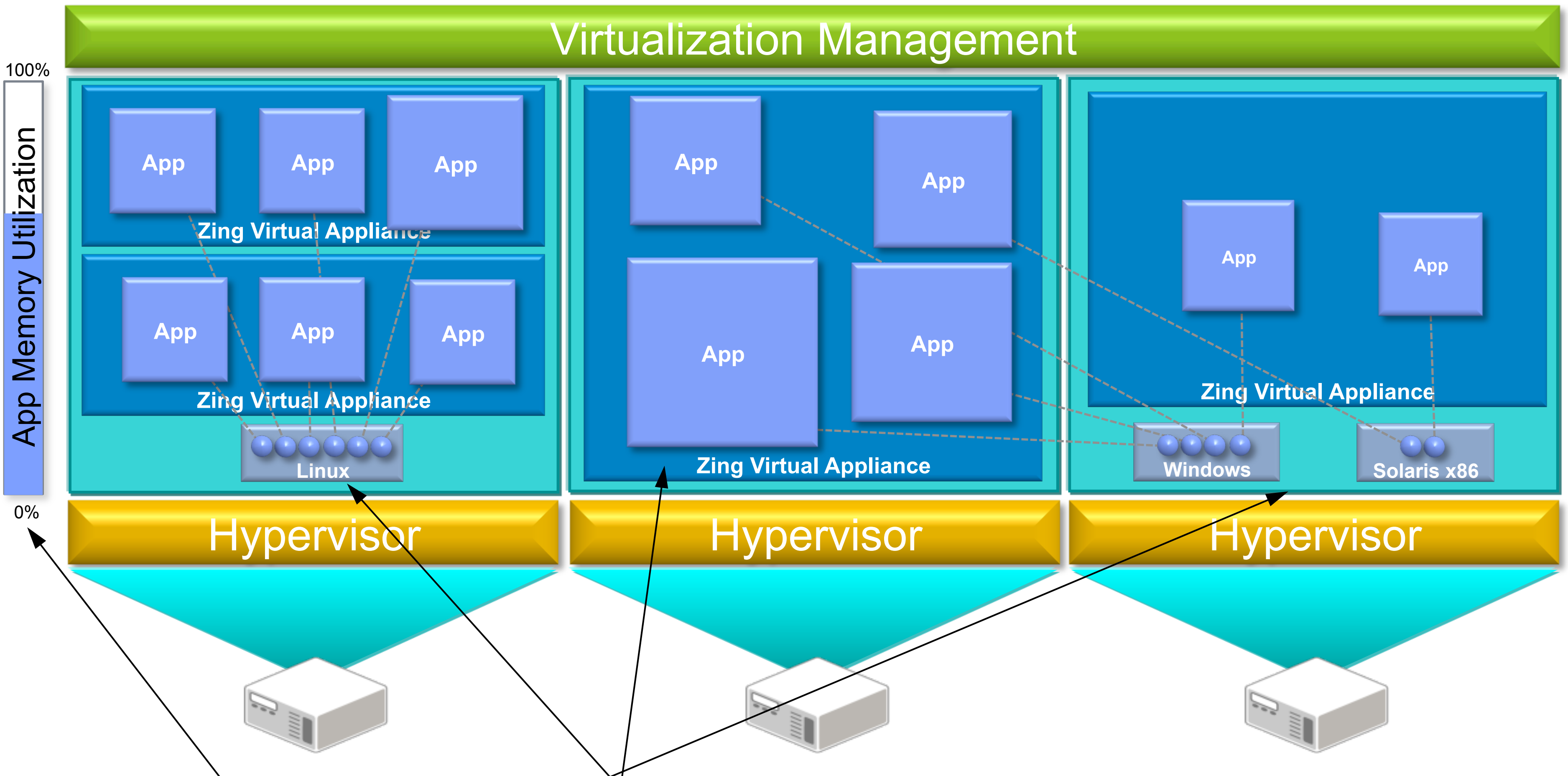
Limited scalability, Too many instances to manage, Inefficient use of resources



~50-100 OS and JVM instances are required to fully utilize a $10K-$20K commodity server.

A Better Way: Zing Elastic Deployments

Elastic app scalability, simplified deployments, efficient use of resources



[illegible] The end result is ***scalable applications, simplified deployments, and efficient use of resources***