The Garbage-First Garbage Collector

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Trademarks And Abbreviations
(to get them out of the way...)

- Java™ Platform, Standard Edition (Java SE)
- Java Hotspot™ Virtual Machine (HotSpot JVM™)
- Solaris™ Operating System (Solaris OS)
- Garbage Collection (GC)
- Concurrent Mark-Sweep Garbage Collector (CMS)
- Garbage-First Garbage Collector (G1)

Who Are These Guys?

- **Tony Printezis**
  - Staff Engineer, HotSpot JVM GC Group
  - Sun Microsystems, Burlington, MA
- **Paul Ciciora**
  - “The Adventurous Customer”
  - Dept Head, Object Oriented Infrastructure
  - Chicago Board Options Exchange (CBOE), Chicago, IL

Learn how **Garbage-First**, aka **G1**, the new low-latency garbage collector in the HotSpot JVM works and what it will mean to your application in the future.

GOAL

Agenda

- Garbage-First Attributes
- Garbage-First Operation
- First Impressions: CBOE
- Final Thoughts

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Java

JavaOne

The Garbage-First Garbage Collector (G1)

- Future CMS Replacement
- Server “Style” Garbage Collector
- Parallel
- Concurrent
- Generational
- Good Throughput
- Compacting
- Improved ease-of-use
- Predictable (though not hard real-time)

The Garbage-First Garbage Collector (G1)

- Future CMS Replacement
- Server "Style" Garbage Collector
- Parallel
- Concurrent
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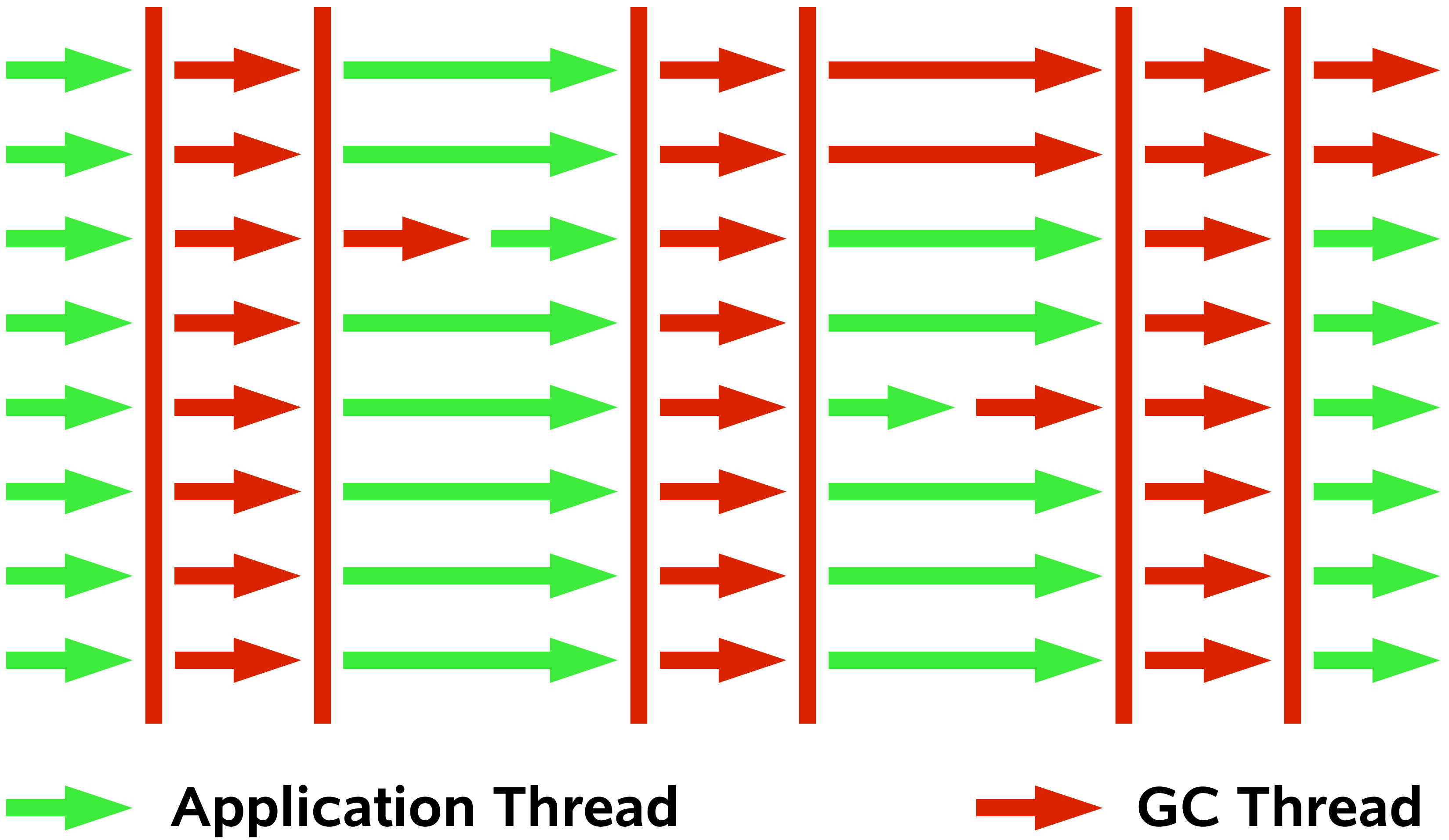
- Good Throughput
- **Compacting**
- **Improved ease-of-use**
- **Predictable (though not hard real-time)**

Main differences between Garbage-First and CMS

GC Work: Parallelism & Concurrency



Predictability

- Cannot guarantee hard real-time behavior
  - OS scheduling
  - Other processes
  - Application behavior (without analysis)
- Soft real-time
  - Achieve good level of predictable behavior
  - With high probability... but no hard guarantees
- If you want hard real-time guarantees, please consider using the Sun Microsystems' Java Real-Time System
- We are expecting G1 to be more predictable than CMS

Compaction

- Consolidates free space in large chunk(s)
- Battles fragmentation
  - Important for long-running applications
  - We can sleep better at night… and in the daytime too. :-)
- Enables fast allocation
  - Linear, no free lists
  - TLABs (thread-local allocation buffers)
  - Infrequent synchronization at allocation time
    - Only at the slow path
- No free lunch!
  - Copying is the largest contributor to pause times

Weak Generational Hypothesis

- Two observations
  - *"Most newly-allocated objects will die young."*
  - *"There are few old-to-young references."*
- Split the heap into "generations"
  - Usually two: young generation / old generation
- Concentrate collection effort on the young generation
  - Good payoff (a lot of space reclaimed) for your collection effort
  - Lower GC overhead
  - Most pauses are short
- Reduced allocation rate into the old generation
  - Young generation acts as a "filter"

Why Generational?

- Most Java applications
  - Conform to the weak generational hypothesis
  - Really benefit from generational GC
  - Performance-wise, generational GC is hard to beat in most cases
- All GCs in the HotSpot JVM are generational

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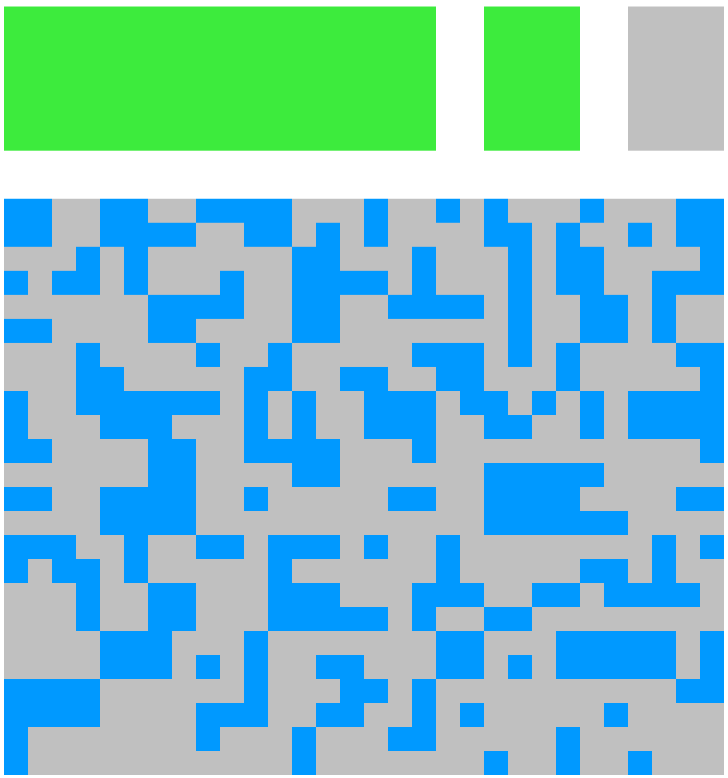
Color Key

- Non-Allocated Space
- Young Generation
- Old Generation
- Recently Copied in Young Generation
- Recently Copied in Old Generation

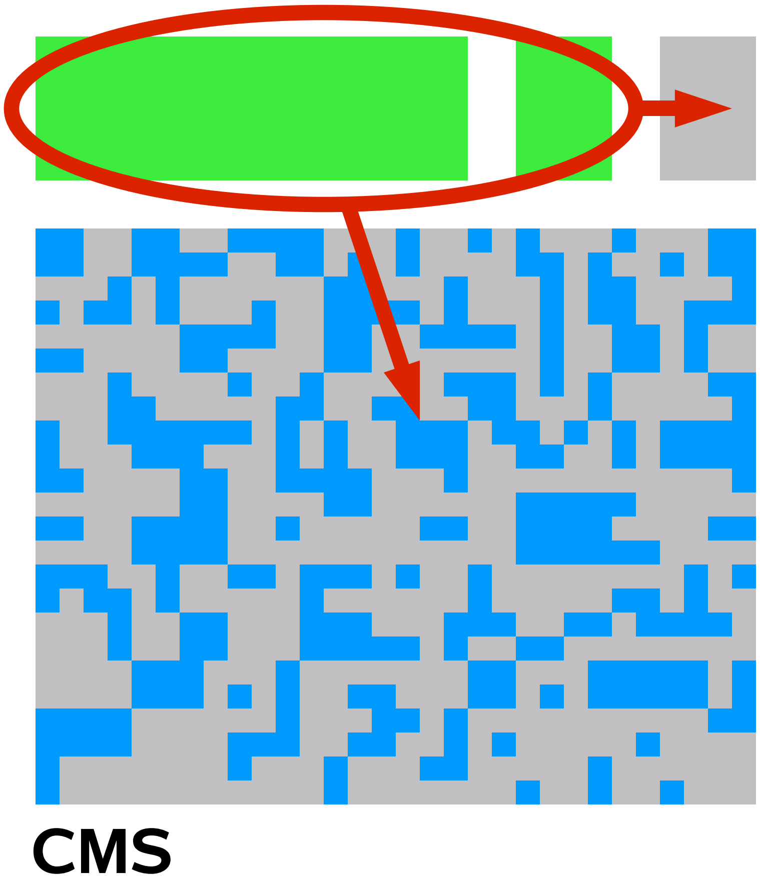
Young GCs in CMS (i)



CMS

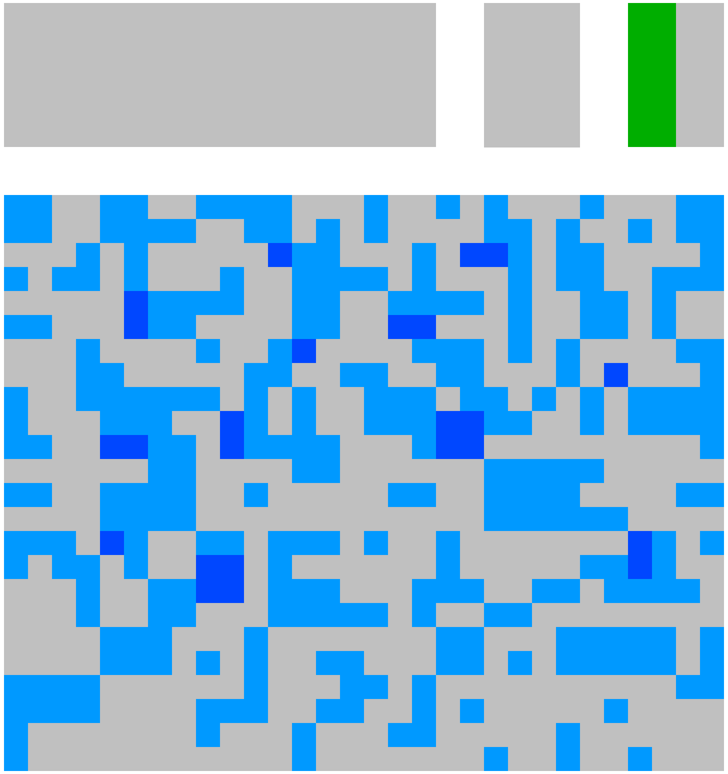
- Young generation, split into
  - Eden
  - Survivor spaces
- Old generation
  - In-place de-allocation
  - Managed by free lists

Young GCs in CMS (ii)



- During a young generation GC
  - Survivors from the young generation are evacuated to
    - Other survivor space
    - Old generation

Young GCs in CMS (iii)

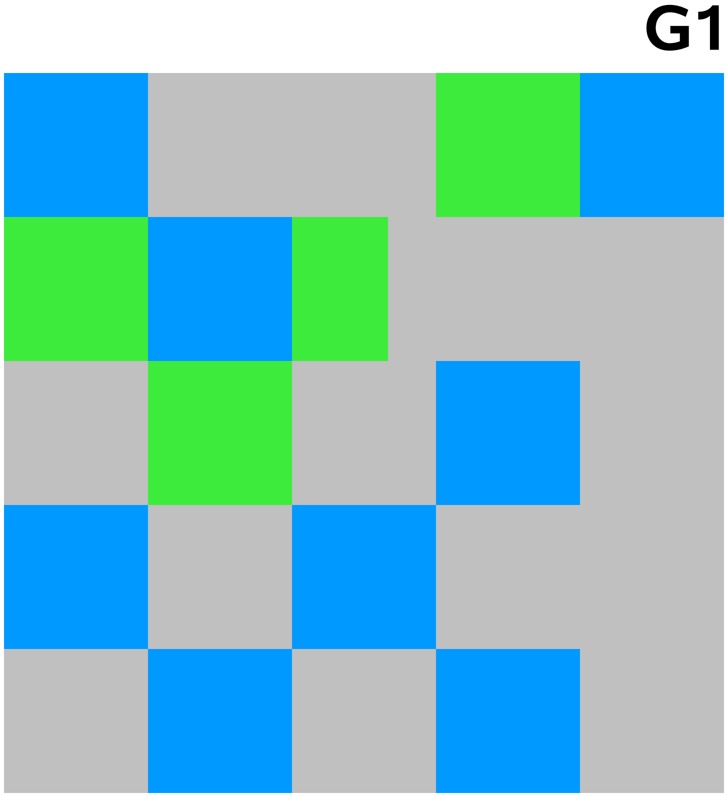


CMS

- End of young generation GC

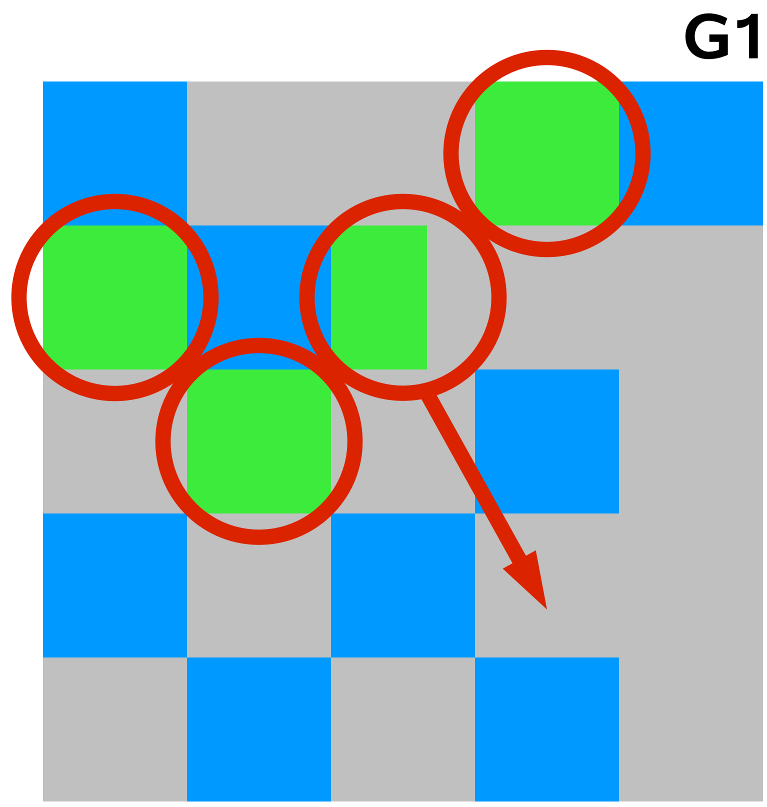
Young GCs in G1 (i)

- Heap split into regions
  - Currently 1MB regions
- Young generation
  - A set of regions
- Old generation
  - A set of regions



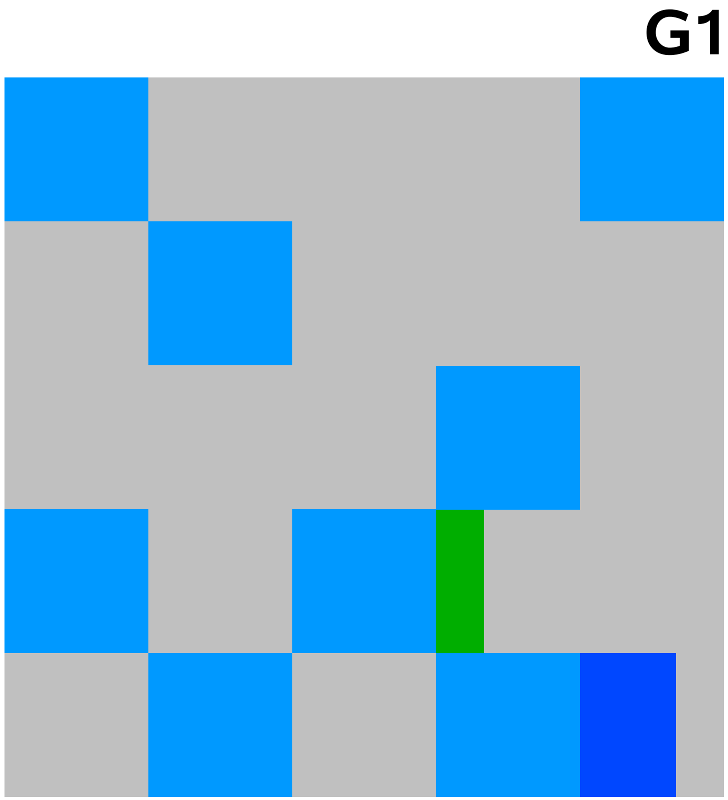
Young GCs in G1 (ii)

- During a young generation GC
  - Survivors from the young regions are evacuated to:
    - Survivor regions
    - Old regions



Young GCs in G1 (iii)

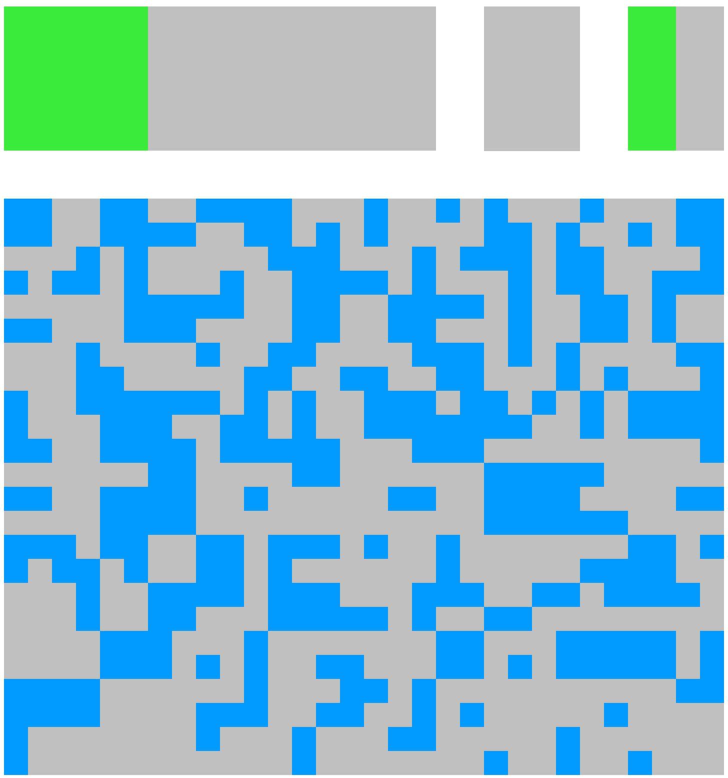
- End of young generation GC



Summary: Young GCs in G1

- Single physical heap, split into regions
  - Set of contiguous regions allocated for large (“humongous”) objects
- No physically separate young generation
  - A set of (non-contiguous) regions
  - Very easy to resize
- Young GCs
  - Done with “evacuation pauses”
  - Stop-the-world
  - Parallel
  - Evacuate surviving objects from one set of regions to another

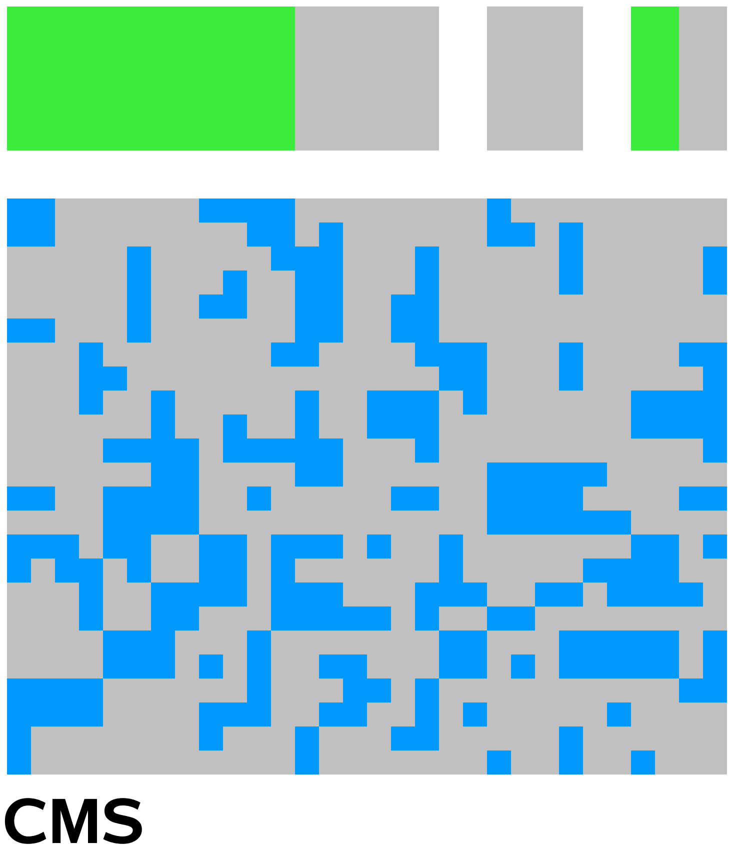
Old GCs in CMS (Sweeping After Marking) (i)



CMS

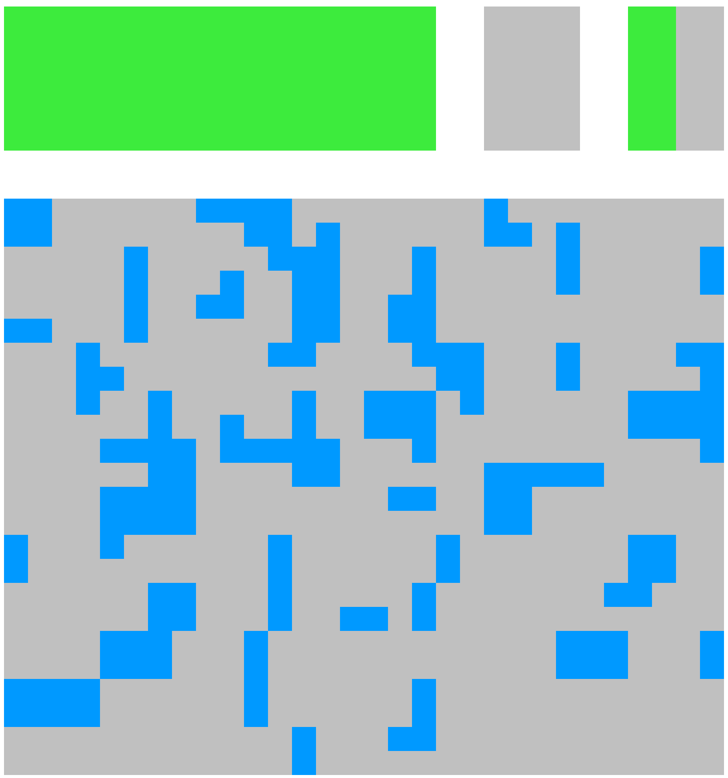
- Concurrent marking phase
  - Two stop-the-world pauses
    - Initial mark
    - Remark
  - Marks reachable (live) objects
  - Unmarked objects are deduced to be unreachable (dead)

Old GCs in CMS (Sweeping After Marking) (ii)



- Concurrent sweeping phase
  - Sweeps over the heap
  - In-place de-allocates unmarked objects

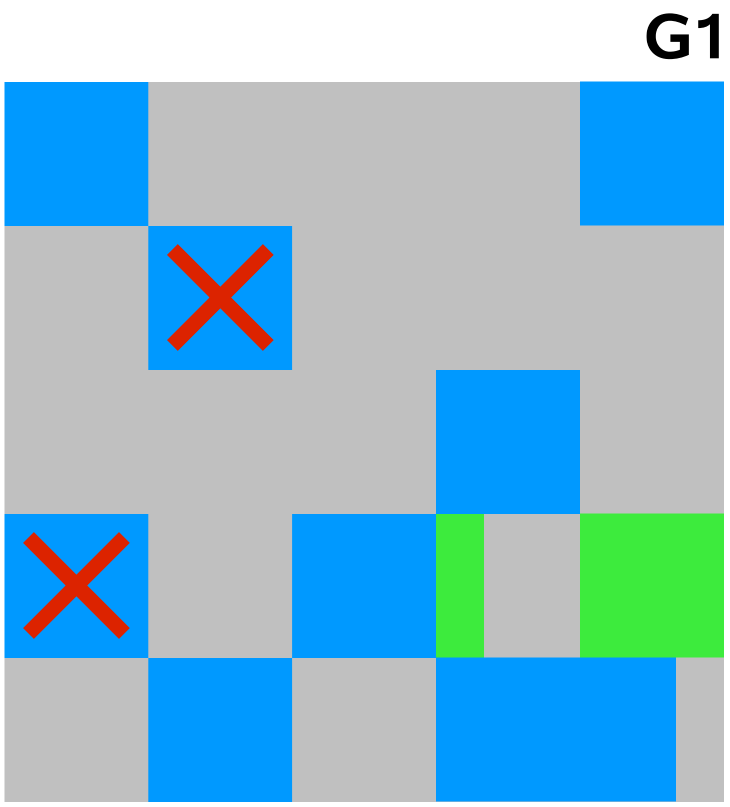
Old GCs in CMS (Sweeping After Marking) (iii)



- End of concurrent sweeping phase
  - All unmarked objects are de-allocated

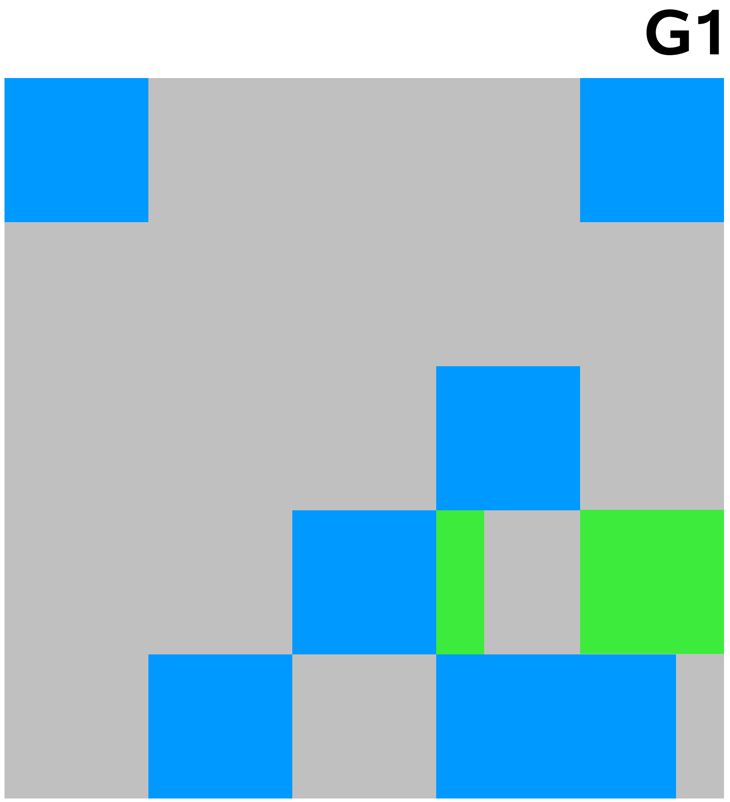
Old GCs in G1 (After Marking) (i)

- Concurrent marking phase
  - One stop-the-world pause
    - Remark
    - (Initial mark piggybacked on an evacuation pause)
  - Calculates liveness information per region
    - Empty regions can be reclaimed immediately



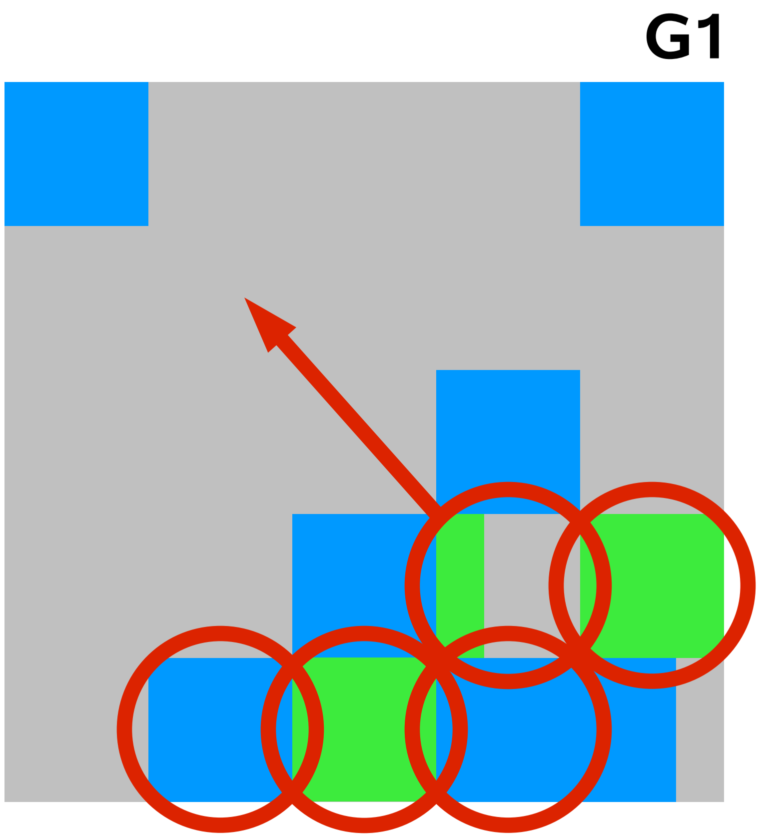
Old GCs in G1 (After Marking) (ii)

- End of remark phase



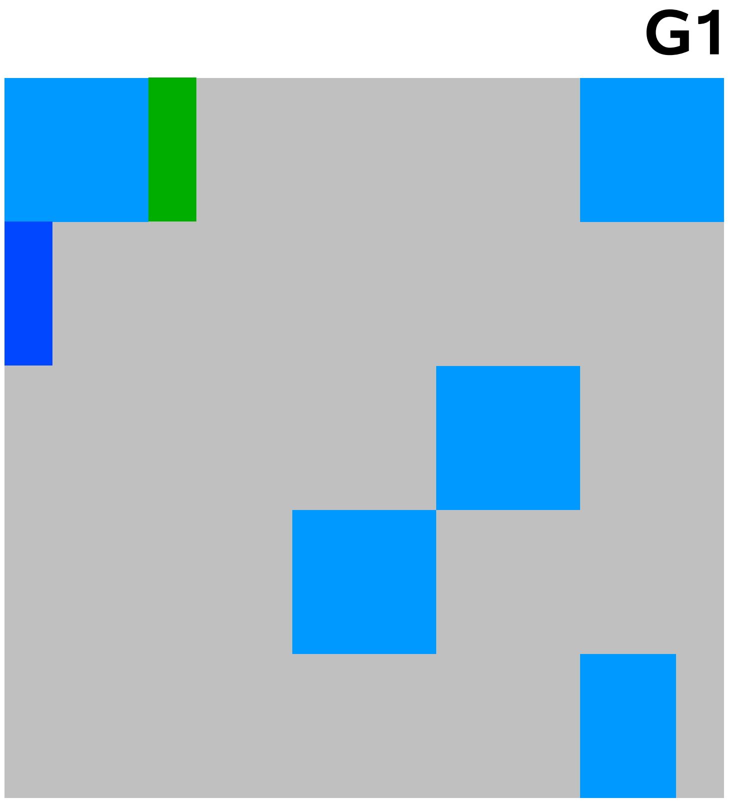
Old GCs in G1 (After Marking) (iii)

- Reclaiming old regions
  - Pick regions with low live ratio
  - Collect them piggy-backed on young GCs
    - Only a few old regions collected per such GC



Old GCs in G1 (After Marking) (iv)

- We might leave some garbage objects in the heap
  - In regions with very high live ratio
  - We might collect them later



Summary: Old GCs in G1

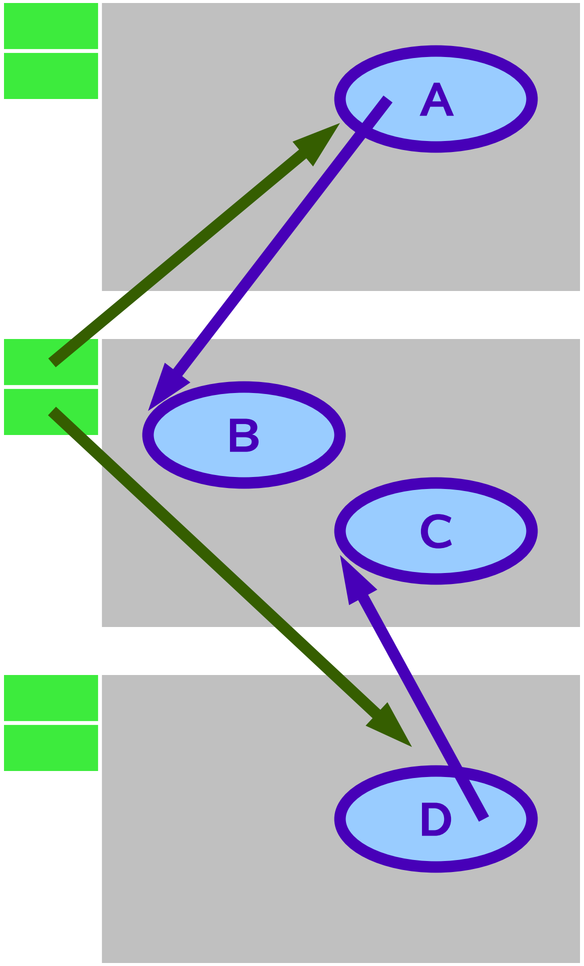
- Concurrent marking phase
  - Calculates liveness information per region
  - Identifies best regions for subsequent evacuation pauses
  - No corresponding sweeping phase
  - Different marking algorithm than CMS
    - Snapshot-at-the-beginning (SATB)
    - Achieves shorter remarks
- Old regions reclaimed by
  - Remark (when totally empty)
  - Evacuation pauses
- Most reclamation happens with evacuation pauses
  - Compaction

G1: “One-And-A-Half” GCs

- CMS
  - Young generation GCs
  - Old generation concurrent marking and sweeping
- G1
  - Evacuation pauses
    - Both for young and old regions
  - Only concurrent marking

Remembered Sets

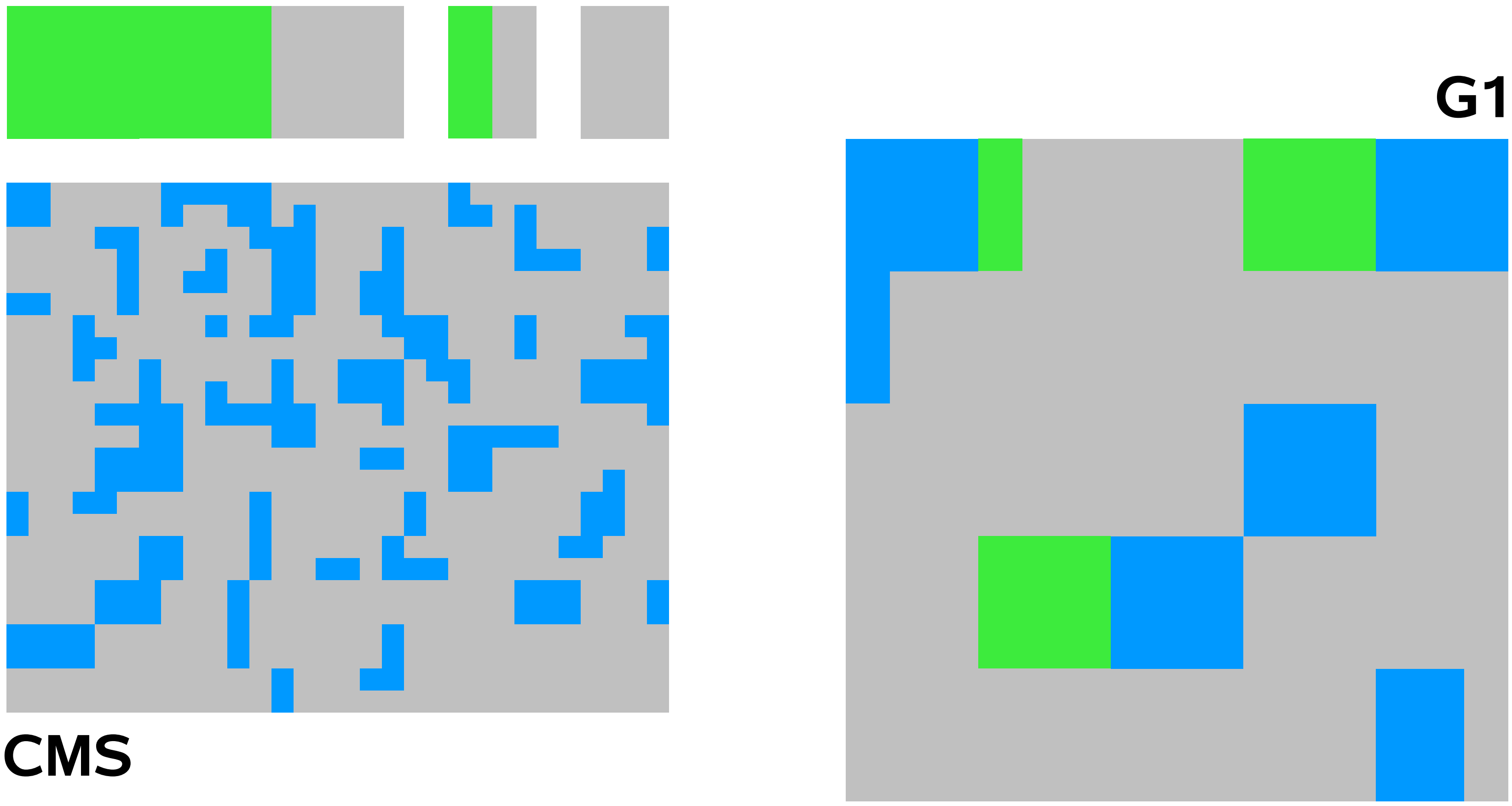
- During evacuation pauses
  - Need to identify “roots” from other regions
- We maintain “remembered sets”
  - One per region
  - Keeps track of all heap locations with references into that region
- We can pick any region to collect
  - Without sweeping the whole heap to find references into it
- Remembered set maintenance
  - Write barrier + concurrent processing
- Remembered set footprint
  - <5% of the heap



Pause Prediction Model

- User-defined pause goal
  - Goal, not a promise or a guarantee!
- Stop-the-world pauses
  - Evacuation pauses are the main “bottleneck”
    - Highly application-dependent
  - Remark pauses are short
- Pause prediction model
  - Keep stats on pause behavior
  - Predict the maximum amount of work that does not violate the goal
    - e.g., young generation size
  - Works best for “steady-state” applications

CMS vs. G1 Comparison



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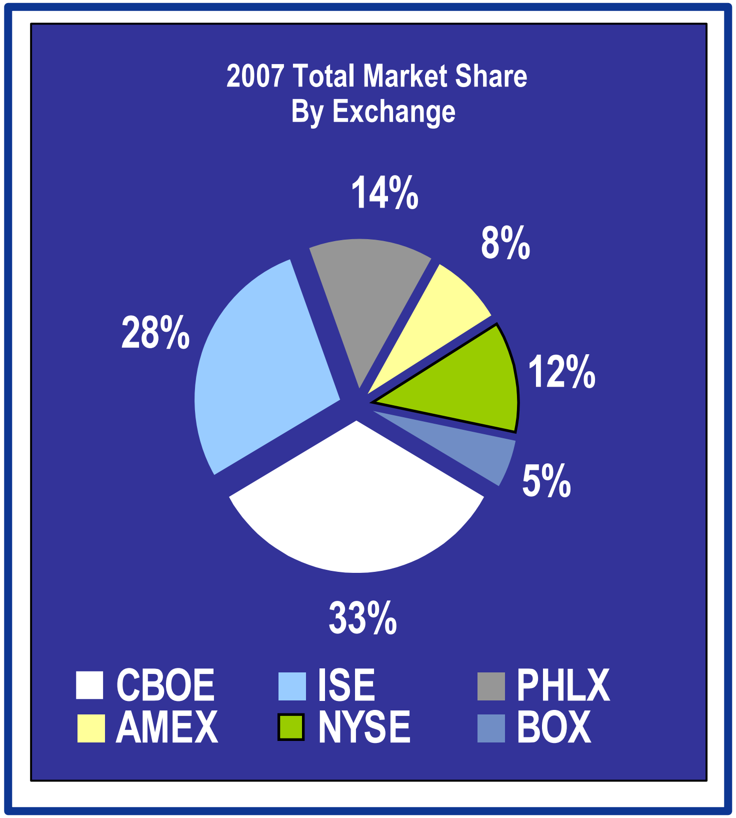
CBOE: Leading the Options Industry for 35 Years

- Founded in 1973, CBOE is the largest U.S. options marketplace
- Original marketplace for standardized, exchange-traded options
- Industry leader in product innovation
- Powered by CBOE*direct*, Hybrid Trading System integrates electronic and open outcry trading, offering unparalleled trading choice
- Launched CBOE Futures Exchange (CFE) in March 2004

CBOE Leads the Industry in Market Share

- CBOE is the number 1 U.S. options marketplace, handling one-third of total industry volume in 2007
- CBOE 2007 market share numbers:
  - Total options: 33.0%
  - Equity options: 25.7%
  - Multiply-listed index/ETF options: 36.7%
  - Cash index options: 86.1%



Profile of the Adventurous Customer
...in a hyper-competitive industry!

- Started tuning GC with 1.2 SemiSpaces
- Early adopter of Parallel Young Gen GC
- Switched to CMS with 1.4.2
- Started testing the Java platform on the Solaris OS 10 x86 in 2005
- Solaris OS 10 x86 in production since May 2006
  - Zones
  - Processor sets
  - FX scheduling
- Currently running 6u4
  - First customer in production
- Leveraging open source

Keeping Current: Effort and Reward

No Pain, No Gain

vs.

Lots of Pain, but Lots of Gain

CBOE Performance Test Environment

How to mitigate the risk of being on the bleeding edge

- Two full production slices, including hardware redundancy
  - Pretesting production software / hardware upgrades
- Two dedicated “wind tunnels”
  - Software / hardware proof-of-concept + GC tuning
  - Heavily virtualized (flexibility)
- ~150 servers
- Personnel
  - 8 full-time staff
  - Running round the clock, on a 20-hour cycle

GC Logging in Production
Turn on the headlights!

- -XX:+PrintGCDetails
- -XX:+PrintGCTimeStamps
- -XX:+PrintHeapAtGC
- -XX:+PrintGCApplicationStoppedTime
- -XX:+PrintGCApplicationConcurrentTime
- -verbose:gc
- -XX:+PrintGCDateStamps
- -XX:+PrintGCTaskTimeStamps
- -XX:PrintCMSStatistics=1
- -XX:+PrintGCTaskTimeStamps
- -XX:+PrintTenuringDistribution
- -XX:PrintFLSStatistics=1

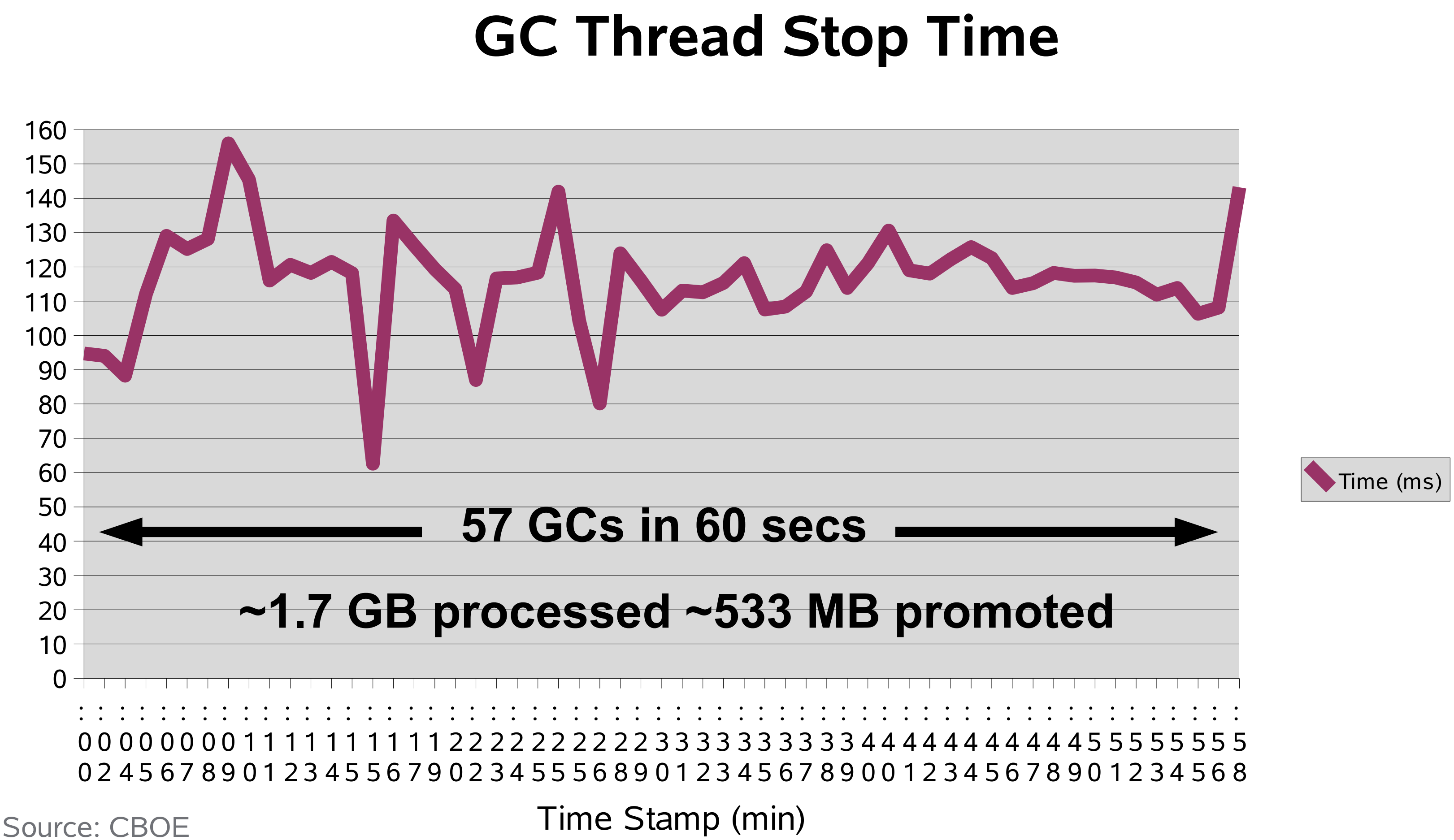
The GC Challenge

- Main objectives
  - Lowering the frequency of the collections
  - Lowering the time of the collections
  - Avoiding a Full GC

The CBOE Problem Set
Worst-case scenario

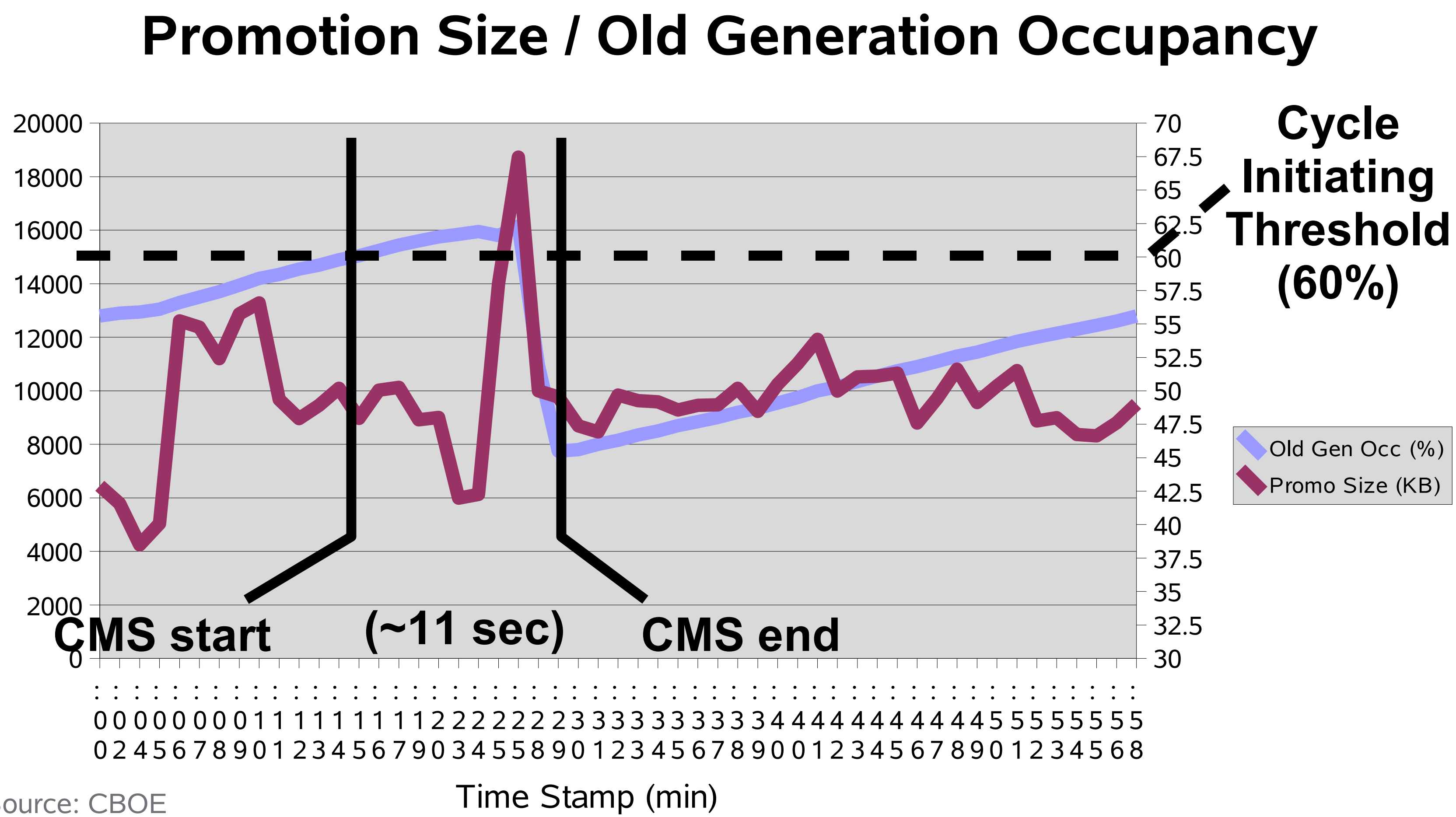
- An average young GC promotes ~6 MBs in ~100 ms at a frequency of ~4 secs
- CMS cycles occur every ~3-4 mins
    - It usually takes ~12-13 secs for a cycle to complete
    - If it does not complete in ~45-50 secs **"we lose the race"**
- Tuning allows for more throughput which just brings us back to the original problem: more garbage!
- The challenge
    - Reduce young GC times to under 50 ms
    - Maintain intervals to > 5 secs
    - Never lose the race

CMS GC Pauses



Source: CBOE

The CMS Obstacle Course



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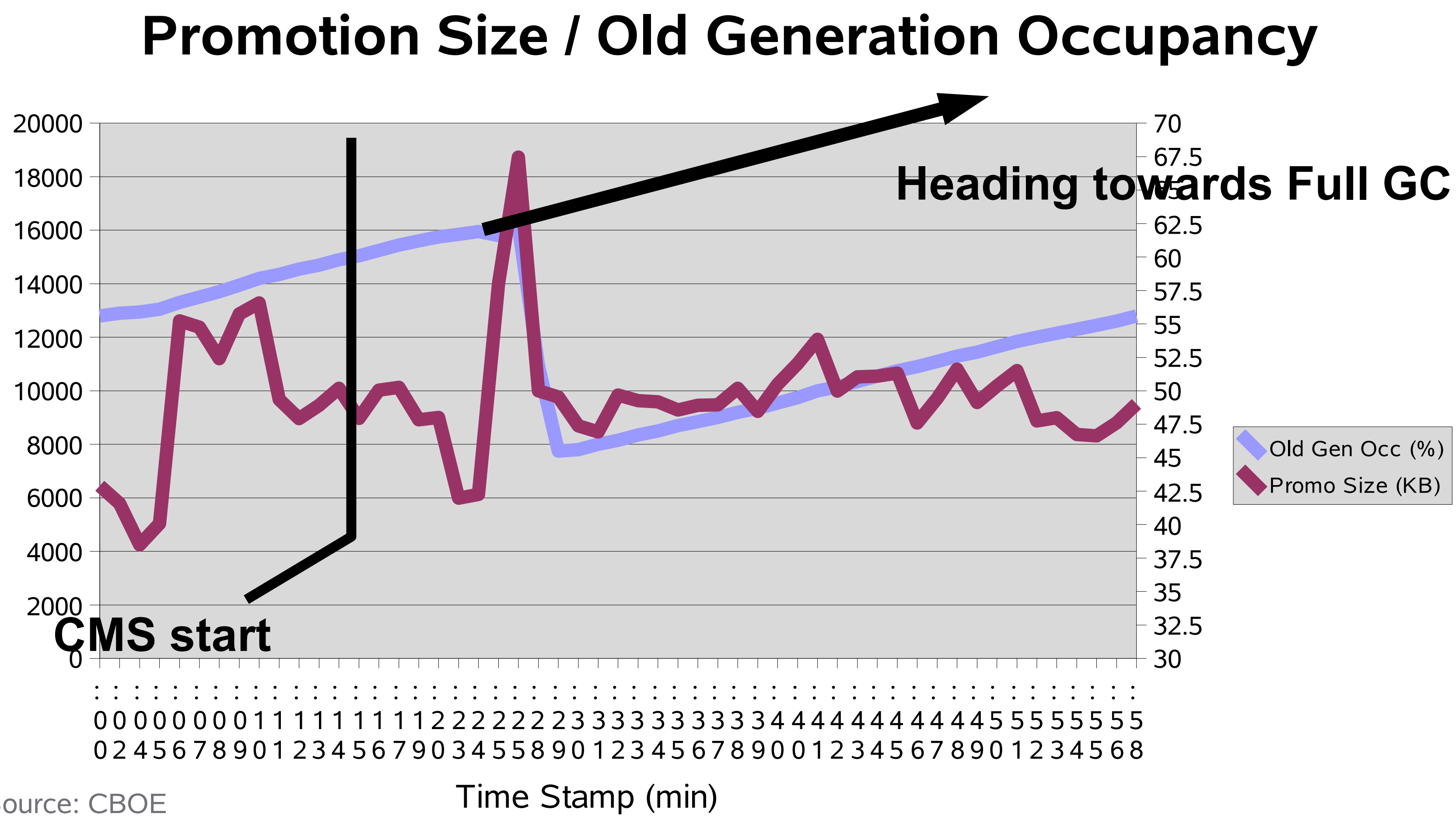

Source: CBOE

CMS vs. G1 Results

- Homogeneous stress test at 3,000 TPS steady
  - Sun Fire™ server X4450, 16-way, 32 GB memory, 32-bit version
- Preliminary Results
  - Achieved a good measure of stability
    - We can run a lot longer than we could 3 months ago. :-)
  - Currently, pause times quite higher than CMS
    - Due to some “band-aids” to address some concurrency-related bugs
  - SATB works as advertised
    - Remarks consistently down to 12ms from 50-60ms with CMS
  - The adventurous customer very satisfied with the G1 GC output
    - Very detailed breakdown to identify tuning opportunities
  - GC team very receptive to “constructive criticism”

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G1 Summary

- Server-Style Low-Latency GC
  - Parallel
  - Concurrent
  - Compacting
  - Soft Real-Time
- Future replacement for CMS

Future Directions

- Reduce
  - Stop-the-world pause times
  - GC overhead
- Deal with mostly-static heap subsets
  - Automatically discover a mostly-static set of regions
  - Reduce marking overhead for that set
  - Target: large caches
- Keep taking advantage of Paul's “wind tunnels” :-)

Reading Material

- D. L. Detlefs, C. H. Flood, S. Heller, and T. Printezis. *Garbage-First Garbage Collection*. In A. Diwan, editor, *Proceedings of the 2004 International Symposium on Memory Management (ISMM 2004)*, pages 37-48, Vancouver, Canada, October 2004. ACM Press.
- T. Printezis and D. L. Detlefs. *A Generational Mostly-Concurrent Garbage Collector*. In A. L. Hosking, editor, *Proceedings of the 2000 International Symposium on Memory Management (ISMM 2000)*, pages 134-154, Minneapolis, MN, USA, October 2000. ACM Press.

THANK YOU

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