RED HAT SUMMIT

Taking out the Trash!

The G1 Garbage Collector Overview for Everyone

@mattjrobson

Matthew Robson
Senior Technical Account Manager

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Today’s Goals

- ✓ What’s *your* role?
- ✓ How does it *work*?
- ✓ Why is it making those *decisions*?
- ✓ Which *logs* are useful?
- ✓ Addressing the most *common problems*

G1 is...

A Java Garbage Collector

- Dynamic
- Generational
- Region Based
- Non-Contiguous
- Parallel
- Multi-Phased
- Incrementally Compacting
- Fully Evacuating
- Garbage First

Your Role

G1 Has Goals

How can I help?

- Keep it simple - Predictable Pause Times
  - Soft target defined by **MaxGCPauseMillis**
  - How many regions are collectible within my target
- Consistent Throughput
  - Maintain a predictable number of transactions per second
- Find the Balance - Understand Your Application!
  - **Low Latency / Time Sensitive** = Lower Max Pause Time
    - Absolutely cannot tolerate application disruption
  - **High Throughput / Lots of Data** = Higher Max Pause Time
    - Push as much data as fast as we can; longer pauses are not a problem

Do what's necessary - In the time defined - Irrespective of the overall Heap Size

G1 Has Goals

How can I hinder?

- Unlike other collectors, G1 set out to simplify parameters and tuning options
  - The more you set, the less G1 is able to do dynamically
- Start out simple; do not carry over settings from other collectors
  - ✓ Enable G1
  - ✓ Set **Xms=Xmx**
  - ✓ Define a pause target
  - ✓ Turn on lots of GC logging
  - ✓ Test
  - ✓ Tune
  - ✓ Repeat

There is no definitive guide or magic set of options; you are responsible for evaluating performance, making incremental changes and re-evaluating until you reach your goals

The *How* and The *Why*

(with some sweet *logs*)

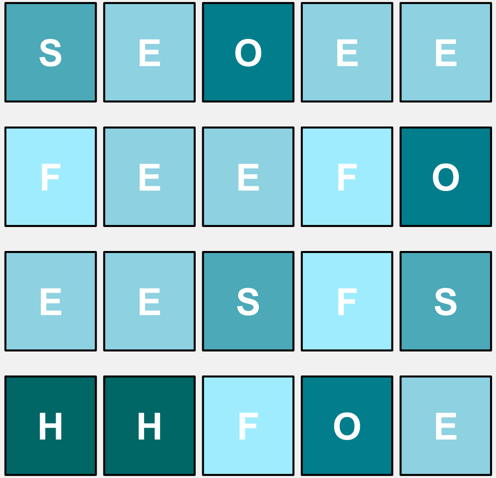
Regions

Understand me, before you change me

- 5 Region Types - (E)**den**, (S)**urvivor**, (O)**ld**, (H)**umongous** and (F)**ree**
- Breaks the heap into ~2048 Regions
- Power of ^{2} from 1 to 32MB

12 GB Heap	
12288 / 2048 Regions	6 MB - not a power of 2
12288 / 8MB Region	1536 Regions - too low
12288 / 4MB Region	3072 Regions - acceptable

- Explicitly set through **G1HeapRegionSize**
  - Fewer Regions means less flexibility
  - Longer to scan, mark and copy



S	E	O	E	E
F	E	E	F	O
E	E	S	F	S
H	H	F	O	E

Why Regions?

And what are they?

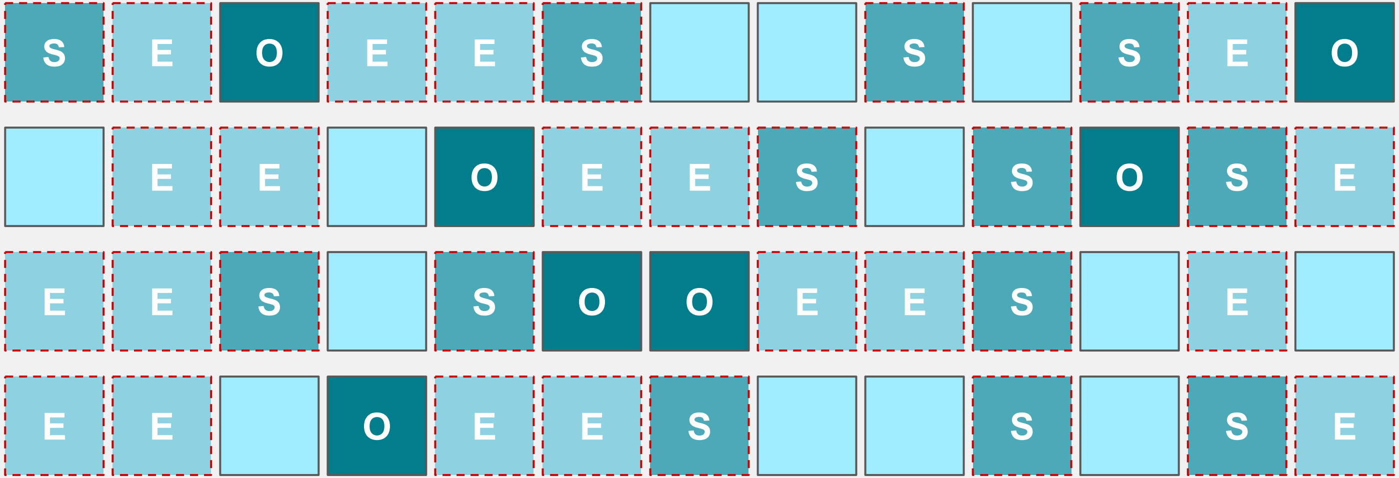
A Region represents a **block of allocated space** that can hold **objects of any generation without** the need to **maintain contiguity** with other **Regions** of the **same generation**

- Reduced synchronization
  - Regions are allocated through a Thread Local Allocation Buffer (TLAB)
  - Object allocation can happen within a TLAB without additional synchronization
- Reduced fragmentation
  - Guaranteed evacuation of Young Regions
  - Incremental and Concurrent compaction of Old Regions
- Dynamic
  - Number of Young Regions is proportional to what’s collectable within the pause target
  - Size is adjusted after each collection

Allocation, Evacuation and Promotion

Phase 1 - Young Collection Pause (YC)

- All new objects smaller than 50% of the Region size are allocated in Eden
- Number of Eden Regions defined by what can be collected within the pause target

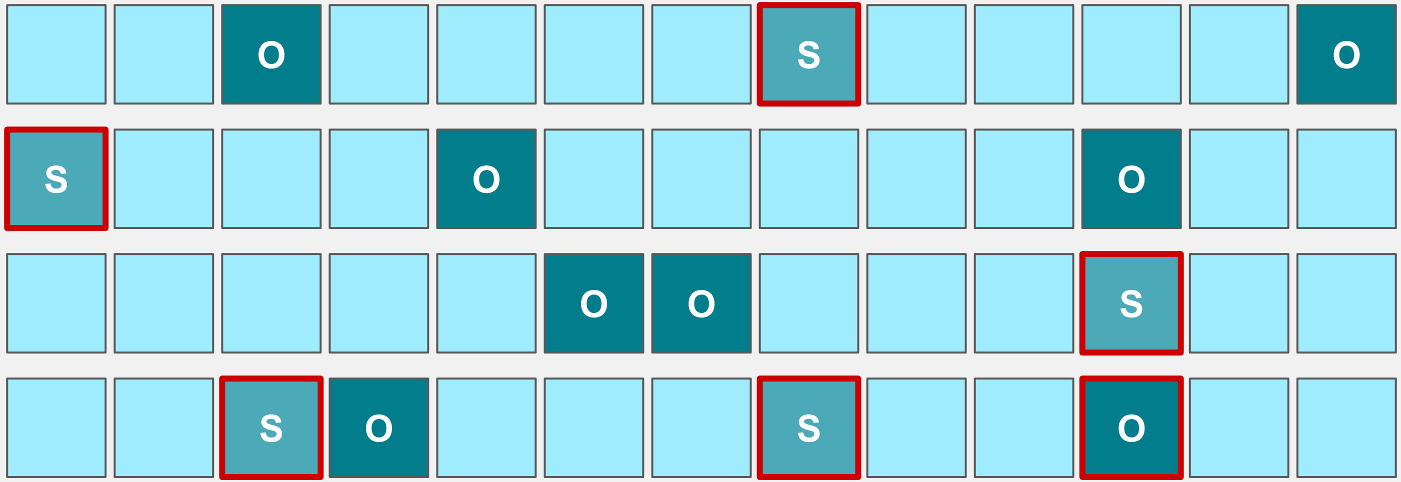


S	E	O	E	E	S			S		S	E	O
	E	E		O	E	E	S		S	O	S	E
E	E	S		S	O	O	E	E	S		E	
E	E		O	E	E	S			S		S	E

Allocation, Evacuation and Promotion

Phase 1 - Young Collection Pause (YC)

- Younger objects are compacted into new Survivor Regions
- Tenured objects are promoted to new Old Regions



		O					S					O
S				O						O		
					O	O				S		
		S	O				S			O		

Young Log

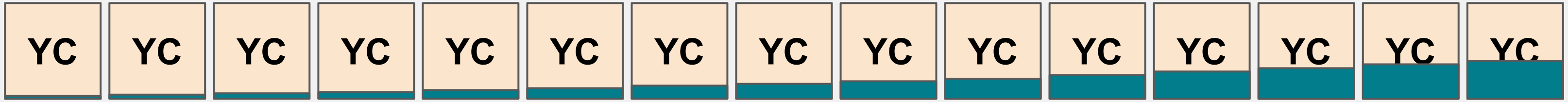
The Most Common Collection

```
2016-12-12T10:40:18.811-0500: 29.959: [GC pause (G1 Evacuation Pause) (young), 0.0305171 secs]
   [Parallel Time: 26.6 ms, GC Workers: 4]
      [GC Worker Start (ms): Min: 29960.0, Avg: 29961.0, Max: 29962.1, Diff: 2.1]
      [Ext Root Scanning (ms): Min: 0.8, Avg: 3.5, Max: 9.7, Diff: 8.9, Sum: 13.9]
      [Update RS (ms): Min: 0.0, Avg: 0.3, Max: 0.4, Diff: 0.4, Sum: 1.1]
         [Processed Buffers: Min: 0, Avg: 66.0, Max: 134, Diff: 134, Sum: 264]
      [Scan RS (ms): Min: 0.3, Avg: 0.3, Max: 0.3, Diff: 0.1, Sum: 1.1]
      [Code Root Scanning (ms): Min: 0.0, Avg: 0.0, Max: 0.0, Diff: 0.0, Sum: 0.0]
      [Object Copy (ms): Min: 15.8, Avg: 19.0, Max: 20.4, Diff: 4.7, Sum: 76.1]
      [Termination (ms): Min: 0.0, Avg: 1.8, Max: 2.9, Diff: 2.9, Sum: 7.3]
         [Termination Attempts: Min: 1, Avg: 1.0, Max: 1, Diff: 0, Sum: 4]
      [GC Worker Other (ms): Min: 0.0, Avg: 0.0, Max: 0.0, Diff: 0.0, Sum: 0.1]
      [GC Worker Total (ms): Min: 23.7, Avg: 24.9, Max: 26.5, Diff: 2.8, Sum: 99.8]
      [GC Worker End (ms): Min: 29985.8, Avg: 29986.0, Max: 29986.5, Diff: 0.7]
   [Code Root Fixup: 0.0 ms]
   [Code Root Purge: 0.0 ms]
   [Clear CT: 0.3 ms]
   [Other: 3.7 ms]
      [Choose CSet: 0.0 ms]
      [Ref Proc: 1.4 ms]
      [Ref Enq: 0.0 ms]
      [Redirty Cards: 0.0 ms]
      [Humongous Register: 0.1 ms]
      [Humongous Reclaim: 0.0 ms]
      [Free CSet: 0.5 ms]
   [Eden: 1097.0M(1097.0M)->0.0B(967.0M) Survivors: 13.0M->139.0M Heap: 1694.4M(2048.0M)->736.3M(2048.0M)]
 [Times: user=0.08 sys=0.00, real=0.03 secs]
```

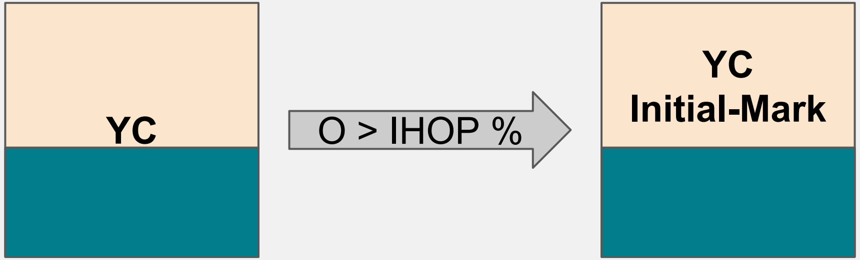
Occupancy

Phase 1 Transition

- Old occupancy will continue to grow as Tenured objects are promoted



- At the end of each Young Collection (YC), non-Young occupancy is evaluated against the **InitiatingHeapOccupancyPercent** (IHOP) (45% default)
- Known as the 'soft-margin', passing the IHOP threshold triggers Concurrent Marking



Young Ergonomics

-XX:+PrintAdaptiveSizePolicy - Why is it doing that?

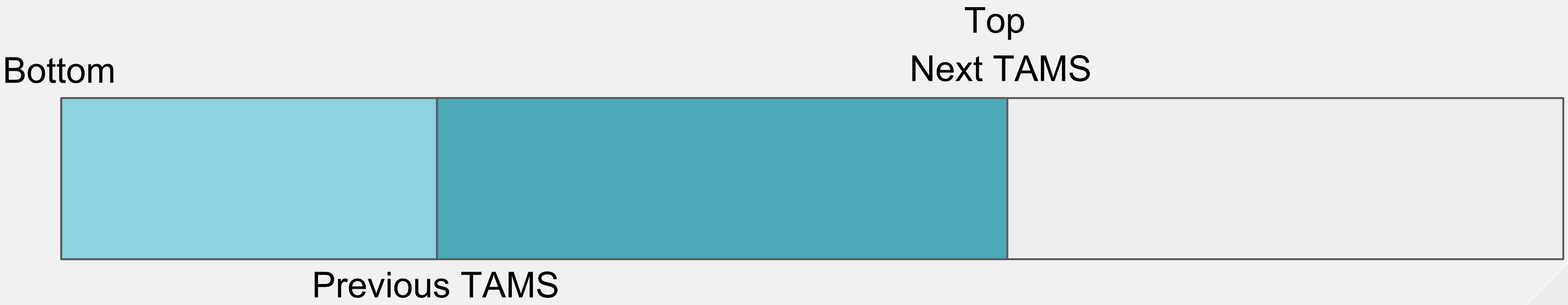
```
2016-12-30T13:28:18.343-0500: 130.629: [GC pause (G1 Evacuation Pause) (young)
 130.629: [G1Ergonomics (CSet Construction) start choosing CSet, _pending_cards: 1792, predicted base time: 2.98 ms,
remaining time: 197.02 ms, target pause time: 200.00 ms]

 130.629: [G1Ergonomics (CSet Construction) add young regions to CSet, eden: 664 regions, survivors: 112 regions,
predicted young region time: 90.15 ms]

 130.629: [G1Ergonomics (CSet Construction) finish choosing CSet, eden: 664 regions, survivors: 112 regions, old: 0 regions,
predicted pause time: 93.13 ms, target pause time: 200.00 ms]

 130.655: [G1Ergonomics (Concurrent Cycles) request concurrent cycle initiation, reason: occupancy
higher than threshold, occupancy: 1013972992 bytes, allocation request: 0 bytes, threshold: 966367620
bytes (45.00 %), source: end of GC], 0.0266860 secs]

227.306: [G1Ergonomics (Concurrent Cycles) request concurrent cycle initiation, reason: occupancy higher than threshold,
occupancy: 115343360 bytes, allocation request: 530800 bytes, threshold: 115133625 bytes (45.00 %), source:
concurrent humongous allocation]
```

Initial Mark

Phase 2 - Where do I start?

- Stop The World Pause piggybacked on a Young Collection
- Marks all root objects
- Top At Mark Start (TAMS) is set to the current top of each regions

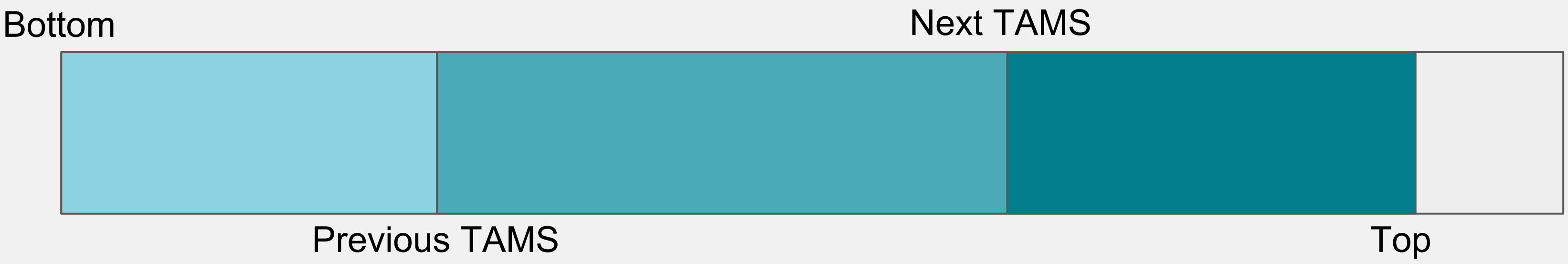
```
130.726: [G1Ergonomics (Concurrent Cycles) initiate concurrent cycle, reason:
concurrent cycle initiation requested]
```



Concurrent Marking

Phase 2 - What’s the catch?

- Based on a Snapshot-At-The-Beginning (SATB) principal
  - Only objects which exist at the time of the snapshot may be identified as garbage
  - Newly allocated objects are implicitly marked live (above the Next TAMS)
  - Calculates the necessary live data information to collect “Garbage First”



Concurrent Marking Log

🟩 CONCURRENT

🟥 STOP THE WORLD

```
2016-12-12T10:40:08.363-0500: 19.510: [GC pause (G1 Evacuation Pause) (young)
        (initial-mark), 0.0387872 secs]
```

```
2016-12-12T10:40:08.402-0500: 19.549: [GC concurrent-root-region-scan-start]
2016-12-12T10:40:08.405-0500: 19.552: [GC concurrent-root-region-scan-end, 0.0030613 secs]
```

```
2016-12-12T10:40:08.405-0500: 19.553: [GC concurrent-mark-start]
2016-12-12T10:40:08.711-0500: 19.858: [GC concurrent-mark-end, 0.3055438 secs]
```

```
2016-12-12T10:40:08.713-0500: 19.861: [GC remark
        2016-12-12T10:40:08.713-0500: 19.861: [Finalize Marking, 0.0014099 secs] 2016-12-12T10:40:08.715-0500:
        19.862: [GC ref-proc, 0.0000480 secs] 2016-12-12T10:40:08.715-0500: 19.862: [Unloading, 0.0025840 secs],
        0.0055136 secs]
        [Times: user=0.01 sys=0.00, real=0.00 secs]
```

```
2016-12-12T10:40:08.724-0500: 19.872: [GC cleanup 1757M->914M(2048M), 0.0023579 secs]
        [Times: user=0.01 sys=0.00, real=0.00 secs]
```

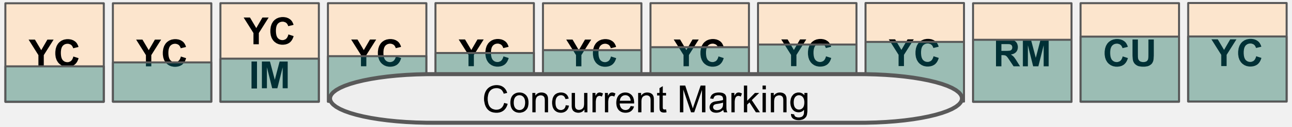
```
2016-12-12T10:40:08.727-0500: 19.875: [GC concurrent-cleanup-start]
2016-12-12T10:40:08.729-0500: 19.876: [GC concurrent-cleanup-end, 0.0012954 secs]
```

Garbage First

Phase 2 Transition

- During **GC Cleanup** the Candidate Old Region list is finalized
  - A Region is a candidate if live objects are < 85% (**G1MixedGCLiveThresholdPercent**)
  - Regions are sorted based on their GC efficiency
- Once CM finishes, an immediate Young Collection occurs
  - Garbage from Old Regions is > 5% (**G1HeapWastePercent**) - Start Mixed Collections

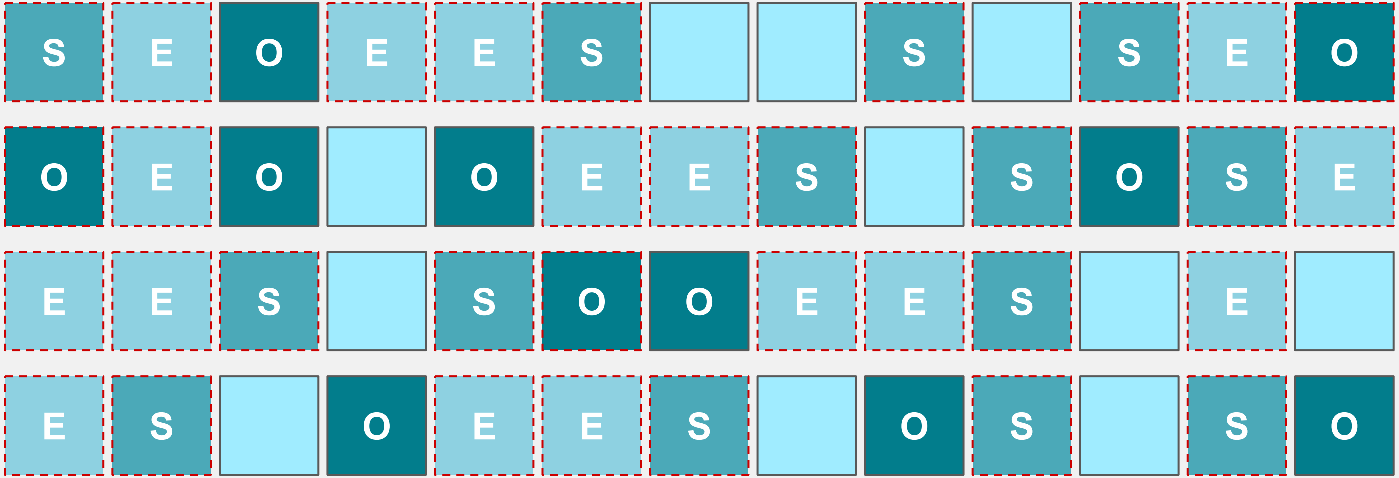
```
2016-12-30T13:28:18.745-0500: 131.030: [GC pause (G1 Evacuation Pause) (young)
 131.051: [G1Ergonomics (Mixed GCs) start mixed GCs, reason: candidate old regions available, candidate
old regions: 740 regions, reclaimable: 485716240 bytes (22.62 %), threshold: 5.00 %], 0.0101749 secs]
```



Mixed Collections

Phase 3 - Mixed Collection Pause (MC)

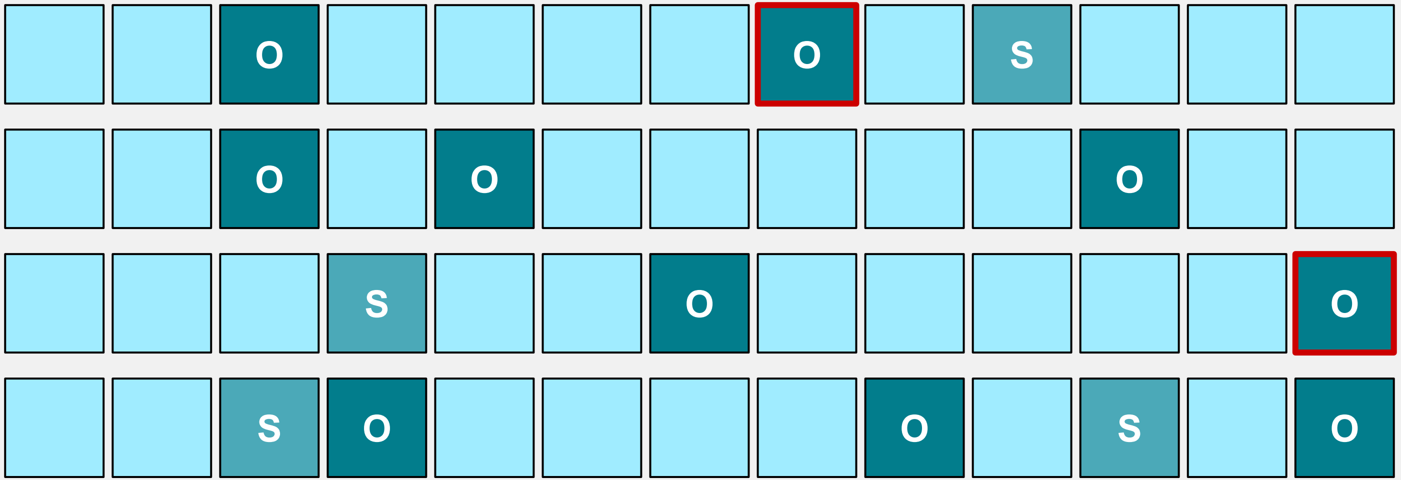
- Mixed Collections are handled incrementally and executed immediately
  - The candidate Old Regions are divided by **G1MixedGCCountTarget** (default 8)
  - Goal is to collect at least that many Old Regions per cycle



Mixed Collections - Incremental Compaction

Phase 3 - Mixed Collection Pause (MC)

- Mixed Collections provide incremental compaction
  - Remaining live objects from the collected Old Regions are copied into to new ‘highly live’ regions



Mixed Ergonomics

What’s up with the Old?

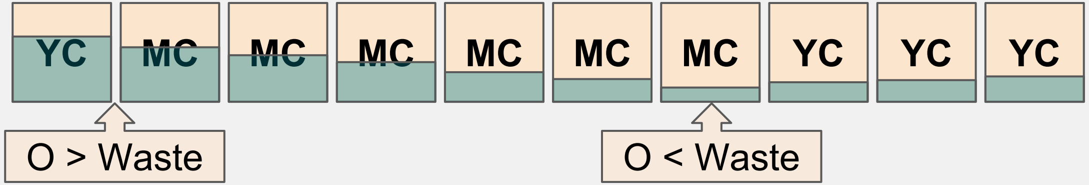
```
2016-12-30T13:28:18.777-0500: 131.063: [GC pause (G1 Evacuation Pause) (mixed)

 131.063: [G1Ergonomics (CSet Construction) start choosing CSet, _pending_cards: 1061, predicted base time: 2.66 ms, remaining time: 197.34 ms,
target pause time: 200.00 ms]
 131.063: [G1Ergonomics (CSet Construction) add young regions to CSet, eden: 89 regions, survivors: 13 regions, predicted young region time:
11.28 ms]

 131.063: [G1Ergonomics (CSet Construction) finish adding old regions to CSet, reason: old
CSet region num reached max, old: 205 regions, max: 205 regions]

 131.063: [G1Ergonomics (CSet Construction) finish choosing CSet, eden: 89 regions, survivors:
13 regions, old: 205 regions, predicted pause time: 19.04 ms, target pause time: 200.00 ms]

 131.073: [G1Ergonomics (Mixed GCs) continue mixed GCs, reason: candidate old regions
available, candidate old regions: 535 regions, reclaimable: 305363768 bytes (14.22 %),
threshold: 5.00 %], 0.0141132 secs]
```

Mixed Collections

Phase 3 Transition

- Collections continue until garbage drops below **G1HeapWastePercent** or 8 iterations

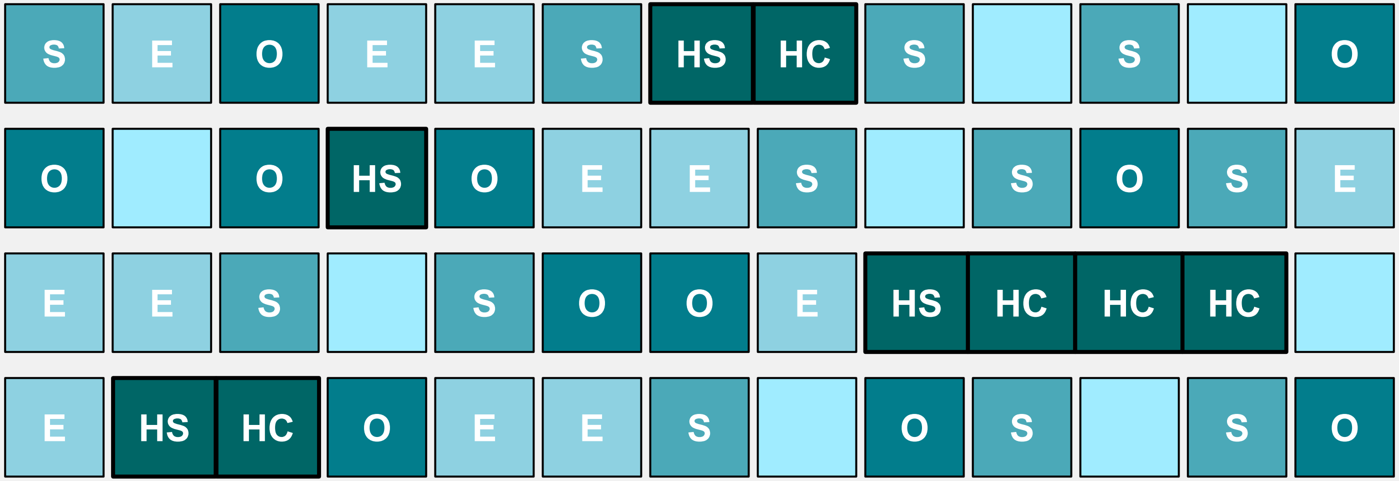
```
2016-12-30T13:28:18.877-0500: 131.163: [GC pause (G1 Evacuation Pause) (mixed)

 131.187: [G1Ergonomics (Mixed GCs) do not continue mixed GCs, reason: reclaimable
percentage not over threshold, candidate old regions: 254 regions, reclaimable: 107174304
bytes (4.99 %), threshold: 5.00 %], 0.0172178 secs]
```



Humongous Allocation

My object is so big, I cannot lie, a single young region, I shall not try

- Any object larger than 50% of a single Region
  - Allocated directly to Old and tagged as Humongous Start / Continues
- An object larger than a single Region must be allocated into contiguous free Regions



S	E	O	E	E	S	HS	HC	S		S		O
O		O	HS	O	E	E	S		S	O	S	E
E	E	S		S	O	O	E	HS	HC	HC	HC	
E	HS	HC	O	E	E	S		O	S		S	O

Full GC

Why oh why, a Full GC, did my collector try?

- Same implementation as the Serial Collector
  - Single Threaded
  - Stop The World
- Collects all Regions
- Fully Compacting
- Guarantees all garbage will be removed
- May shrink (**MaxHeapFreeRatio**) or expand (**MinHeapFreeRatio**) the heap if you do not have Xms=Xmx

Full GC Ergonomics

Why is it doing that?

```
106.445: [G1Ergonomics (Heap Sizing) attempt heap expansion, reason: allocation request failed, allocation request: 24 bytes]

106.445: [G1Ergonomics (Heap Sizing) expand the heap, requested expansion amount: 1048576 bytes, attempted expansion amount: 1048576 bytes]

106.445: [G1Ergonomics (Heap Sizing) did not expand the heap, reason: heap already fully expanded]
2016-12-30T13:27:54.160-0500: 106.445: [Full GC (Allocation Failure)
 106.539: [G1Ergonomics (Heap Sizing) attempt heap shrinking, reason: capacity higher than max desired capacity after Full GC, capacity: 2147483648 bytes, occupancy: 391145472 bytes, max desired capacity: 1303818239 bytes (70.00 %)]
 106.570: [G1Ergonomics (Heap Sizing) shrink the heap, requested shrinking amount: 843665409 bytes, aligned shrinking amount: 843055104 bytes, attempted shrinking amount: 843055104 bytes]
 2047M->373M(1244M), 0.1278200 secs]
```

Metaspace

The new Perm

- Metaspace lives in native memory and is committed as necessary (non-contiguous)
    - No max size (by default), bound by OS memory and SWAP
    - Grows dynamically until it reaches max size
    - Faster, because it lives in native memory
    - **MetaspaceSize** (high watermark) determines when a collection will happen
        - Depending on the amount freed, the high watermark may increase
- **UseCompressedClassesPointers** creates a separate 1Gig class space
    - **CompressedClassSpaceSize** is reserved in contiguous space at VM initialization
        - This cannot change or grow
    - Committed space counts as part of **MaxMetaspace**

The most *common problems*

7 Common G1 Issues

And where to start

- ✓ Collect and analyze the GC logs
  - ○ **Garbagecat** and **GCViewer** are good options
- ✓ Calculate the size of your Live Data Set
  - ○ At any given time, how much is alive?
- ✓ Calculate your most common large object sizes
  - ○ Does the default **G1HeapRegionSize** align?
- ✓ Evaluate your promotion rate
  - ○ What is dieing young versus what ends up in Old
- ✓ Map Growth of Young and Old Generations over time
  - ○ Is the Eden too compressed?

7 Common G1 Issues

And where to start

1. Promotion Failures / Premature Marking - (to-space exhausted), 0.5669726 secs]

   ☒ Very Long Pause compared to a regular Young Collection

   ☒ Copied objects must be updated

   ☒ Objects which failed to copy are tenured in place (as there are no free Regions)

   ✓ Evaluate Concurrent Marking (**InitiatingHeapOccupancyPercent**)

   ✓ Mixed Collection Effectiveness

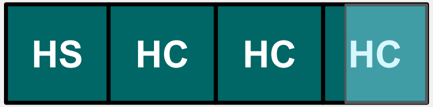
   ✓ Tune Heap Size and Reserve Percentage

Common G1 Issues Cont.

Big Issues from Big Objects

2. Humongous Obj - reason: requested by GC cause GC cause: G1 Humongous Allocation

- ☒ Creates fragmentation
- ☒ Accelerates Old region growth and premature marking
- ✓ Compare and adjust **G1HeapRegionSize** in relation to the average object size
- ✓ Tune Max Heap to better accommodate common object size



Region Size: 4096 K
Object A: 12800 K
Result: 4 regions and 16384 K
Waste: 3584 K

Common G1 Issues Cont.

Full GC Fail

3. Full GC - 3 Most Common Cases:
   a. Full GC (Metadata GC Threshold)
      - ☒ Setting a **MaxMetaspaceSize** that is too small for the workload
      - ☒ **UseCompressedClassesPointers** creating tight Metaspace
      - ☒ Classloader leaks
      - ✓ Tune **Metaspace** for proper sizing and check for leaks

   b. [GC pause (young) (to-space exhausted) and [Full GC]
      - ☒ Heap can no longer be expanded and there are no free regions for evacuation
      - ☒ The **G1ReservePercent** did not provide enough of a promotion buffer
      - ☒ Collector could not recover
      - ✓ Evaluate Concurrent Marking (**IHOP**) and Mixed Collection **effectiveness**
      - ✓ Tune Max Heap Size and Reserve Percentage

Common G1 Issues Cont.

Did you actually mark anything?

c. [GC concurrent-mark-start] and [Full GC] and [GC concurrent-mark-abort]
   - ☒ Running out of heap before Concurrent Marking can finish
   - ☒ Longer lived objects with a promotion rate faster than you can collect
   - ✓ Evaluate when Concurrent Marking **starts** (**InitiatingHeapOccupancyPercent**)
   - ✓ Review how **long** Concurrent Marking takes
   - ✓ Tune Max Heap Size based on your **Live Data Set**

4. Concurrent Marking - [GC concurrent-mark-end, 25.3988906 secs]
   - ☒ Running out of heap before concurrent marking can finish
   - ☒ Not collecting a high percentage of garbage
   - ✓ Large heap and undersized machine - Not enough CPU
   - ✓ Too few concurrent threads - Percentage of Parallel Threads
     - ✓ Increasing **ConcGCThreads** will take away CPU from application threads
   - ✓ Object creation rate leading to many interrupting Young Collections

Common G1 Issues Cont.

Why so slow?

5. Long / Inefficient Mixed Collections
   - ☒ Leads to Full GC
   - ☒ Takes away from Application processing time
   - ✓ Collecting too many inefficient regions? Increase **G1HeapWastePercent**
   - ✓ Not maximizing the full pause time? Increase **G1OldCSetRegionThresholdPercent**
6. Long Update RS
   - ✓ Tune concurrent refinement threads - **G1ConcRefinementThreads**
   - ✓ Tune RSet Update time - **G1RSetUpdatingPauseTimePercent**
   - ✓ Check for working being pushed to mutator threads
7. Long Scan RS
   - ✓ Evaluate the RSet statistics - **G1SummarizeRSetStats**
   - ✓ Check for coarsenings in RSetStats

Useful *Flags*

G1 Flags

Keep it simple and test

Flag	Definition
-XX:+UseG1GC	Enable G1
-XX:MaxGCPauseMillis=200	G1 soft pause target (ms)
-XX:InitiatingHeapOccupancyPercent=45	Soft margin to initiate marking
-XX:G1HeapRegionSize=1m	Region size, as a power of 2
-XX:G1MixedGCCountTarget=8	Target number of mixed collections
-XX:G1MixedGCLiveThresholdPercent=85	Live byte threshold for Old region CSet inclusion
-XX:G1HeapWastePercent=5	Amount of heap to waste to avoid expensive regions
-XX:G1ReservePercent=10	Space reserved for promotion
-XX:G1EagerReclaimHumongousObjects=true	Reclaim Humongous objects with Young GC

G1 Flags Cont.

Keep it simple and test

Flag	Definition
-XX:G1ConcRefinementThreads	Parallel threads for RSet updates
-XX:G1NewSizePercent=5	Set the minimum Young size
-XX:G1MaxNewSizePercent=60	Set the maximum Young size
-XX:G1OldCSetRegionThresholdPercent=10	Max Old regions in CSet as a percent of heap
-XX:G1RSetUpdatingPauseTimePercent=10	Percent of time for Update RS
-XX:SurvivorRatio=8	Ratio of Eden to Survivor space
-XX:MaxTenuringThreshold=15	Number of iterations before promotion to Old
-XX:ParallelGCThreads='logical CPUs'	Parallel STW threads
-XX:ConcGCThreads='25% of Parallel'	Concurrent marking threads

G1 Flags Cont.

Keep it simple and test

Flag	Definition
-XX:MetaspaceSize=	Initial Metaspace high water mark
-XX:MaxMetaspaceSize=unlimited	Max Metaspace size
-XX:CompressedClassSpaceSize=1G	Maximum class area for Compressed Class Pointers
-XX:+UseCompressedOops	Use 32-bit references
-XX:+UseCompressedClassPointers	Use 32-bit class pointers

Logging Flags

Must Use

Flag	Definition
-Xloggc:/path/to/gc.log	Path where the GC logs are written
-XX:+UseGCLogFileRotation	Enable GC log file rotation
-XX:NumberOfGCLogFiles=<value>	Number of rotated GC logs files to retain
-XX:GCLogFileSize=<size>	Size of each GC logs file to initiate rotation
-XX:+PrintGCDetails	Detailed GC log
-XX:+PrintGCDateStamps	Actual date and timestamp of the collection
-XX:+PrintGCApplicationStoppedTime	Amount of time the application stopped during GC
-XX:+PrintGCApplicationConcurrentTime	Amount of time the application ran between GCs
-XX:-PrintCommandLineFlags	Prints all the command line flags in the GC log

Logging Flags

For Testing and Analysis

Flag	Definition
-XX:+PrintAdaptiveSizePolicy	Details about the collector ergonomics
-XX:+PrintTenuringDistribution	Survivor space usage and distribution
-XX:+PrintReferenceGC	Time spent processing references

Logging Flags

For Debug

-XX:+UnlockDiagnosticVMOptions	
-XX:+G1SummarizeConcMark	Summarizes Concurrent Mark at JVM exit
-XX:+G1PrintHeapRegions	Print the heap regions selected for allocation, cleanup, reuse, compact, cset, commit, failure etc...
-XX:+G1PrintRegionLivenessInfo	Prints previous and next liveness data per Old region before and after every concurrent mark cycle
-XX:+G1SummarizeRSetStats -XX:G1SummarizeRSetStatsPeriod=1	Print RSet processing information every X, where X is measured in GC cycles
-XX:+UnlockExperimentalVMOptions	
-XX:G1LogLevel=fine, finer, finest	Increased logging verbosity on collections
-XX:+G1TraceEagerReclaimHumongousObjects	Details about live and dead Humongous objects

Supplemental Resources

TAM Blogging

- Part 1: Detailed G1 Introduction
  - https://www.redhat.com/en/about/blog/part-1-introduction-g1-garbage-collector
- Part 2: Collecting and Reading G1 Garbage Collector Logs
  - Publish Date May 9th
- Part 3: Evaluating and Tuning the G1 Garbage Collector
  - Future
- Part 4: A Look Ahead; G1 Changes in JDK9
  - Future
- TAM Blogging Series
  - https://www.redhat.com/en/about/blog/technical-account-managers

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