

# Effective Software

Lecture 13: Memory Management in JVM – Memory Layout, Garbage Collectors

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- [1] Jones, R., Hosking, A., Moss, E.: The Garbage Collection Handbook. CRC Press, USA 2012.
- [2] JVM source code - <http://openjdk.java.net>
- [3] Oaks, S.: Java Performance: 2<sup>nd</sup> Edition. O'Reilly, USA 2020.

- » Memory management
  - Properties of automated memory management
  - Generational concept
  - Identify reachability of objects
  - Design architecture
- » Parallel collector
  - Remember set
  - Parallel scavenge
  - Parallel mark compact
- » Garbage first collector
  - Properties
  - Minor, mixed, full activities
  - Humongous objects

# Automatic Memory Management

## » **advantages** over explicit memory management

- no crashes due to errors – e.g., usage of de-allocated objects
- no memory leaks

## » components

- parts in **application code**

- allocation
- read/write references

- **garbage collector**

- discovers unreachable objects (not transiently reachable from **roots** – variables and stack operands in frames, static fields, special native references from JNI)
- reclaims garbage

```
New():  
    ref ← allocate()  
    if ref = null  
        collect()  
    ref ← allocate()  
    if ref = null  
        error "Out of memory"  
    return ref
```

# Automatic Memory Management

## » memory management characteristics

- **safety** – never reclaim space of reachable objects, thread-safe
- **throughput** – application code performance
  - allocation performance – avoid fragmentation
  - *handles or direct references*
  - expensive *reference counting* or *cross-region reference tracking*
    - read/write barriers – e.g., added compiled code
  - later reads affected by re-ordering – breaking data locality, false sharing
- **completeness and promptness**
  - eventually all garbage
  - promptness of reclamation – how long garbage occupies memory
- **pause time** – stop the world (global safe point)
- **space overhead**
  - additional cost per capacity/reference
  - double heap for copying
- **scalability and portability** - multicore, large heaps

# Generational Concept

## » **generational hypothesis**

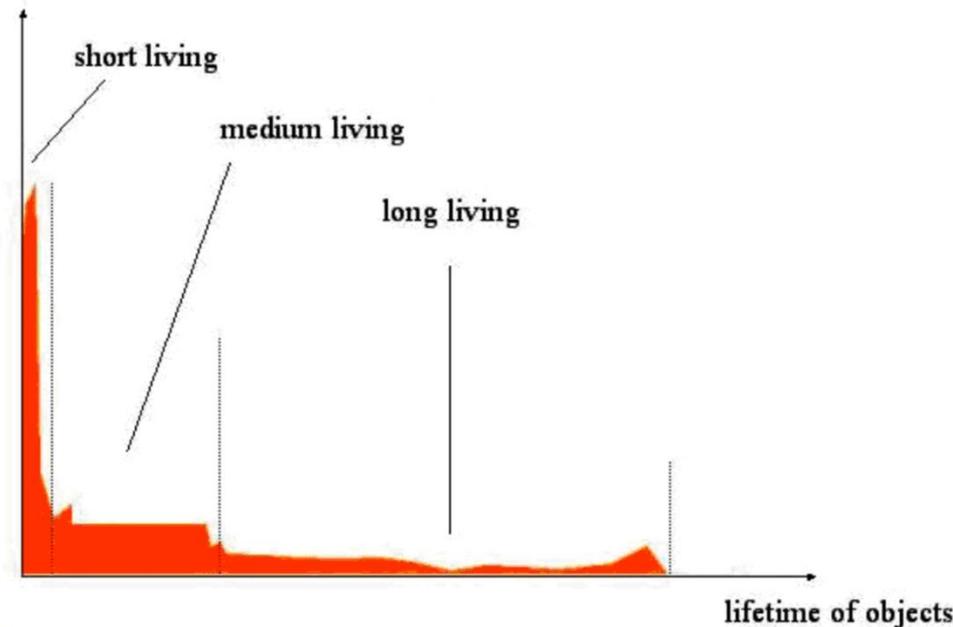
- **weak** – most objects die young
  - there exist few references from older to younger objects
- **strong** – younger object dies earlier than older

## » segregate objects by age into **generations** (JAVA use 2 generations) to **minimize pause time**

- **young**
  - small size
  - frequent fast **minor** collections (milliseconds)
- **old** (tenured)
  - large size
  - rare slow **full** collections (seconds)

## » promotion of objects during minor collections

number of objects



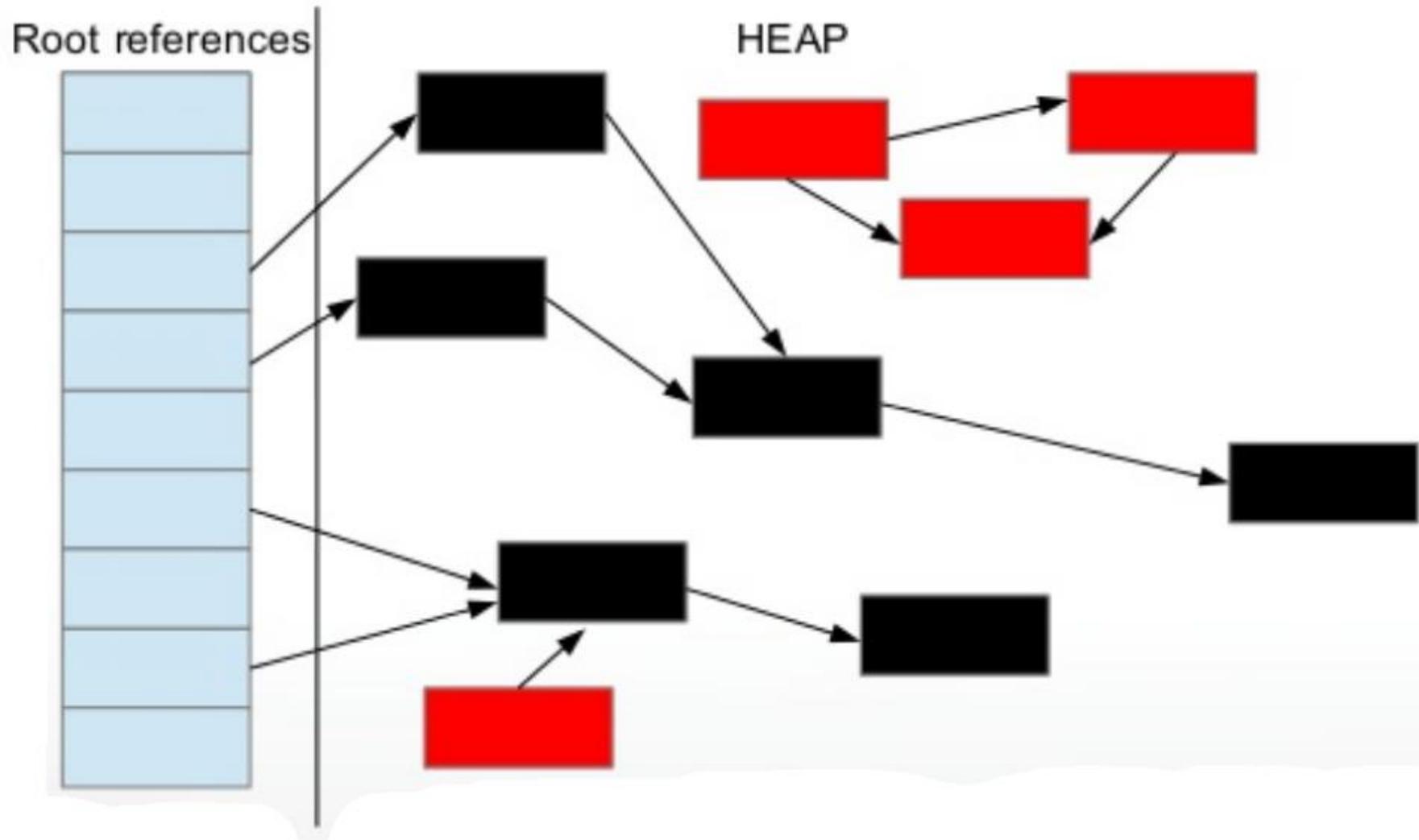


# Identify Reachable Objects – Option 2

## » reference tracing approach

- no direct slow down of application code
  - **find** references
    - root in frames (stack, variables incl. parameters) using **OopMaps**
      - compiled maps for every possible *safepoint* entry
- ```
OopMap{rsi=0op [48]=0op rdx=0op [72]=0op off=1734}
```
- in a different object using object type
    - reference positions in internal Klass VM structure
  - **marking phase** traverse all objects from **roots**
    - depth-first search, breath-first search
    - dominates collection time due to random access to memory
      - cache prefetching to reduce cost
  - use **mark flags** to avoid cycles
    - in object header – standard writes with possible partial re-traversal
    - side bitmaps (1 bit for 64 bits) – improving cache operations, atomics

# Identify Reachable Objects – Reference Tracking

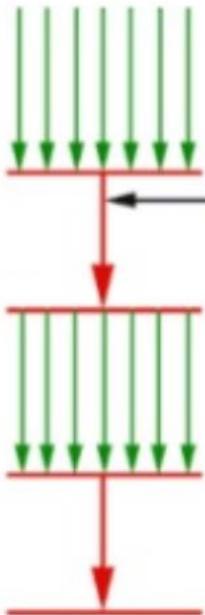


# Garbage Collector Design Architecture

- » *serial* vs. *parallel*
- » *concurrent* vs. *stop the worlds*
- » *compacting/sliding* vs. *non-compacting* vs. *copying*

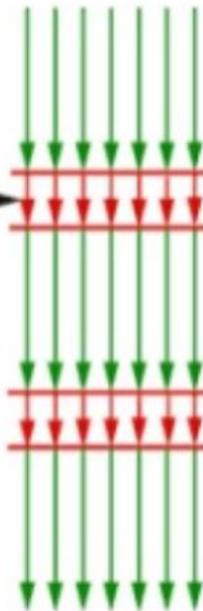


Serial

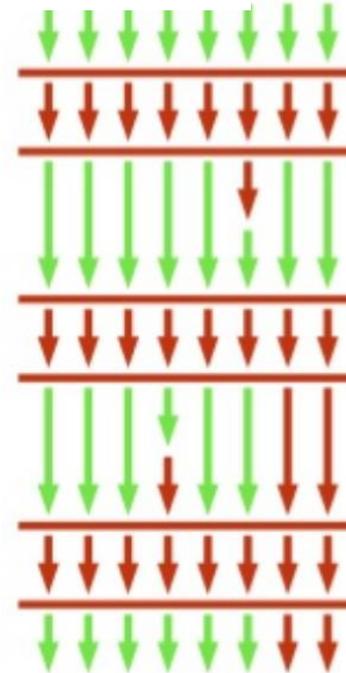


Parallel

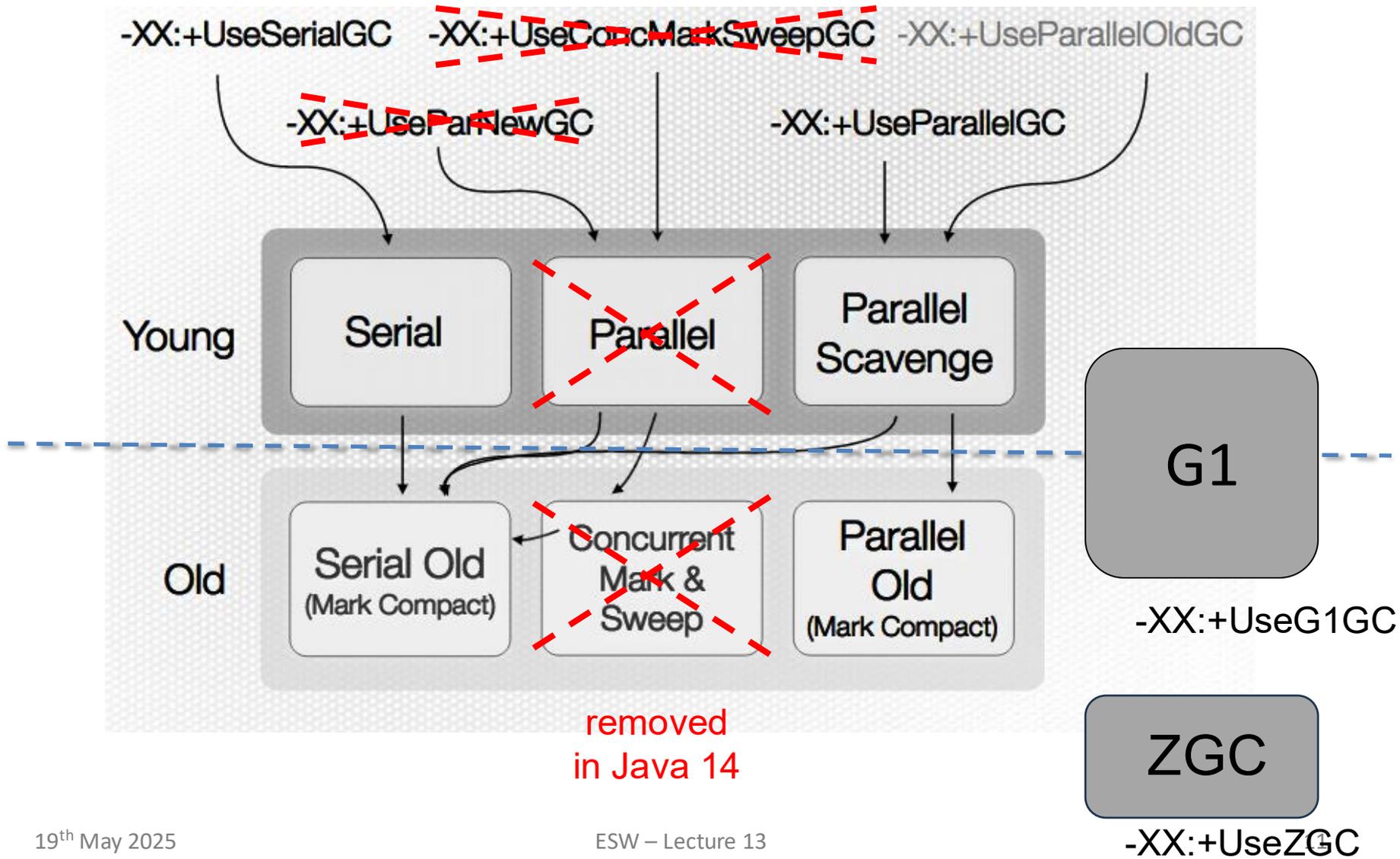
Stop-the-world pause



Garbage-First

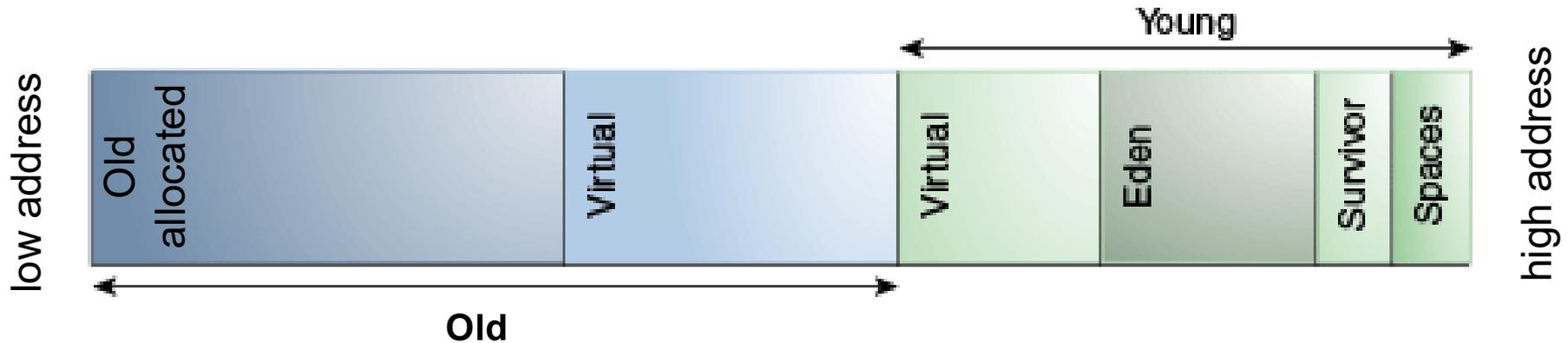


# Garbage Collector Design Architecture



# Parallel Collector

- » **JVM heap layout** supporting adaptive resizing (*virtual* has no physical pages)



- » **max heap** size (virtual space allocated) –Xmx
  - default ¼ RAM up to 25 GB if there is  $\geq 100$  GB RAM
- » **initial heap** size (really allocated) –Xms
  - default 1/64 RAM up to 1 GB if there is  $\geq 128$  GB RAM
- » **Young vs. Old** ratio –XX:NewRatio=<n>
  - default 2 – thus *Old* is 2x larger than *Young*
- » **Survivor** spaces vs. **Eden** ratio –XX:SurvivorRatio=<n>
  - default 8 – thus *Eden* is 8x larger than one *Survivor* space

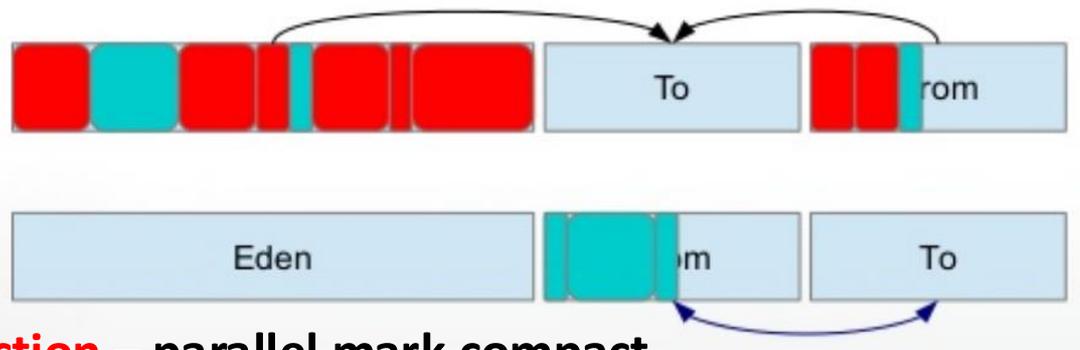
# Parallel Collector

## » object allocations

- in TLAB inside *Eden* – if no space in TLAB left, new TLAB is allocated
- in *Eden* directly for objects larger than TLAB
- in *Old* directly for objects larger than *Eden*

## » minor collection – parallel scavenge

- triggered when there is no space for new TLAB/object in *Eden*
- collection in the *Young* generation only, promotes to *Survivor* or *Old*
- results into clean *Eden*, **swap** of active *Survivor* space (one empty)

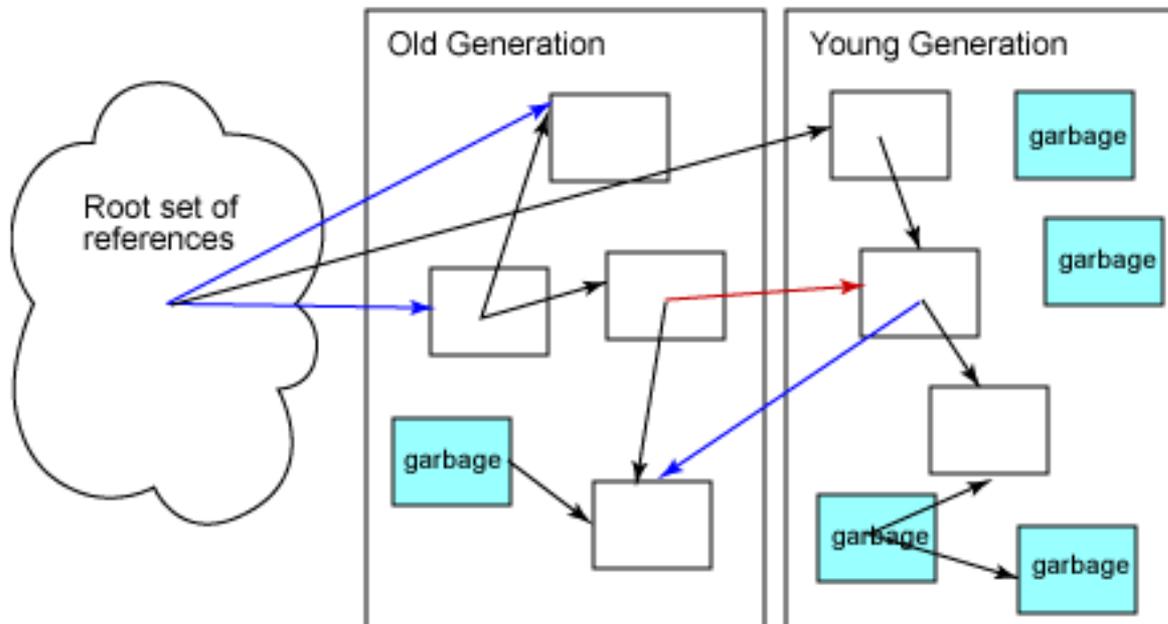


## » full collection – parallel mark compact

- triggered when there is no space for promotion or a new object in *Old*
- collection in *Young* and *Old* generations
- results into completely clean *Young* (*Eden*, both *Survivor* spaces)

# Remembered Set

- » **track old-to-young references**
- » **speeds-up** frequent identification of reachable objects for **minor collection**
  - marking phase starts from **roots** and **references old-to-young**
  - do not traverse objects out of *Young* generation
    - fast bit operations using generation size  $2^n$



**red** – old-to-young, **blue** – to old (*don't need to trace during minor collection*)

# Card Table Compressed Remembered Set

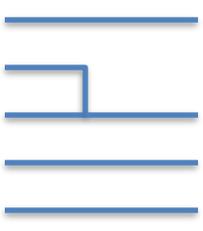
- » whole heap divided to **512 Bytes chunks** (8 cache lines of 64 Bytes)
  - each chunk has one card table slot
- » thread-safe **card table** is Byte based
  - avoids expensive atomic read-update-write for bit operations
  - standard byte writes
    - **dirty** (0) – possibly contain reference to *Young* (has false positive)
    - **clean** – cannot contain reference to *Young* (no false negatives)
  - 100 GB heap => 200 MB card table (<0.2%)
    - one cache line holds cards for 32kB of heap
- » *write reference to object* implies **assembly code write barrier**
  - no tracking for null writes or reference writes in newly allocated objects
  - tracks **standard object start address** `CARD_TABLE[object address >> 9] = 0;`
  - tracks **real element address for native reference arrays**  
`CARD_TABLE[array slot address >> 9] = 0;`
  - **imprecise but very fast** without any condition
    - tracks *Young* generation references only, all reference writes

# Card Table Compressed Remembered Set – Write Barriers

write non-null reference in RAX to **standard object** at R11, standard OOP, 64-bit:

```

mov    %rax,0x10(%r11)
mov    %r11,%r8
shr    $0x9,%r8
movabs $0x215153000,%r9
movb   $0x0,(%r9,%r8,1)
    
```

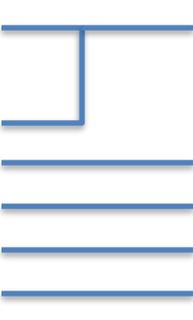


store reference in RAX to the first field in the object  
 compute card offset from obj. start (R11) directly  
**card table** start address to R9  
 store **dirty** flag to the card table

write non-null reference in RAX to **array** at R10 index EBP, standard OOP, 64-bit:

```

movslq %ebp,%r11
shl    $0x3,%r11
lea    0x18(%r10,%r11,1),%r11
mov    %rax,(%r11)
shr    $0x9,%r11
movabs $0x215153000,%r8
movb   $0x0,(%r8,%r11,1)
    
```



count address of the slot in the array to R11  
 store reference in RAX to the array slot  
 compute card offset from slot address (R11)  
**card table** start address to R9  
 store **dirty** flag to the card table

Native Object array structure  
 standard OOP, 64-bit:

|       |                             |               |
|-------|-----------------------------|---------------|
| 0x00: | mark word                   |               |
|       | Klass ref.                  |               |
| 0x10: | array length                | empty padding |
|       | object reference on index 0 |               |
| 0x20: | object reference on index 1 |               |

# Card Table Compressed Remembered Set – Write Barriers

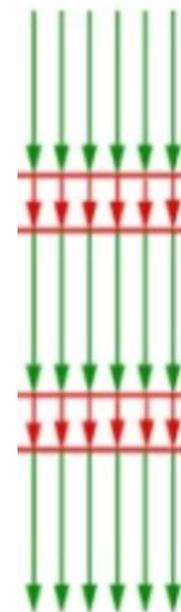
- » **no optimization** for multi reference writes to the same object (which is fast due to already cached part of the card table)
  - object can overlap over 512 Bytes chunk boundary
- » **false sharing** in contended multi-thread writes (even worse on multi-CPU)
  - 64B cache line implies sharing of cards for 32kB of Heap (64\*512)
  - speed-up with **conditional card table updates** (-XX:+UseCondCardMark)

```
if (CARD_TABLE [address >> 9] != 0) CARD_TABLE [address >> 9] = 0;
```

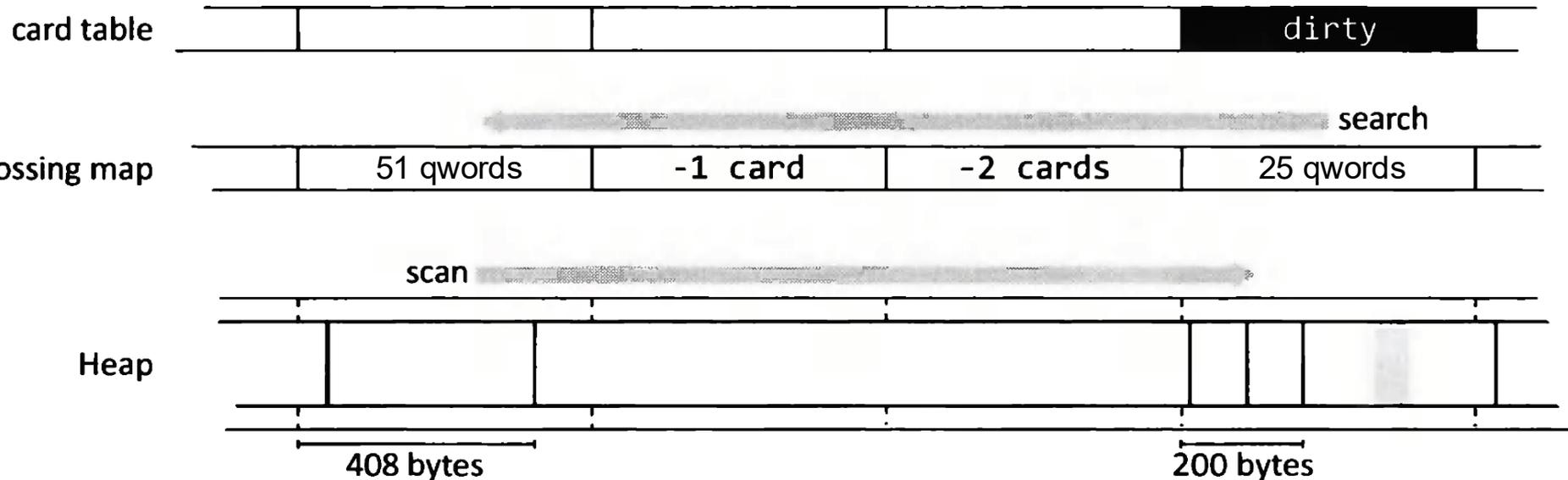
– for highly contended reference writes up to 7 times faster

# Minor Collector – Parallel Scavenge

- » known also as **throughput garbage collector**
- » default for Oracle JVM 8
- » utilize more cores/CPU's (-XX:ParallelGCThreads=<N>)
  - default #HW threads for  $\leq 8$
  - $3 + 5/8$  of #HW threads otherwise (e.g., 13 for 16 threads)
- » stop-the-world manner
- » **copying** with *Survivor* spaces (“from” and “to” are swapped)
  - relocate reachable objects in *Young* generation to “to” *Survivor*
    - if no space, relocate them to *Old* (or trigger full collection)
  - *Eden* and “from” *Survivor* space is empty after the minor collection
- » **parallel processing** of **task queue** initially filled with
  - stripes of cards for searching for old-to-young references (only allocated)
  - JNI handles and VM internal references
  - frames from stacks of all threads
  - static references



# Minor Collector – Scan Old for References to Young



- » **crossing map** - Byte per 512 Bytes chunk like card table, for **old only**
  - updated during allocation/promotion of object and full collection
  - **speed-up search for object start**
    - N>0 object start offset in align positions of the last object in the card
    - N<0 object start offset start -N cards back or the there is the next -N
- » **clean cards** before **DFS** queuing of **processing of addresses of old-to-young refs**
  - already **forwarded objects** are updated immediately without queuing
  - -XX:PrefetchScanIntervalInBytes=576 (9 cache lines)

# Minor Collector – Process Address of –to-Young Reference

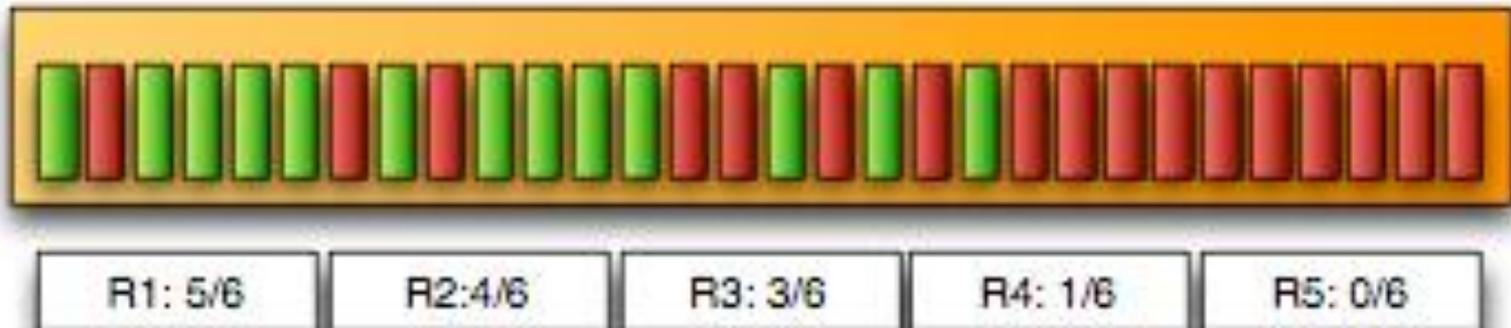
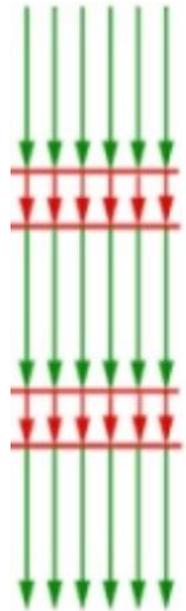
- » target is already **marked/forwarded** – mark word (forwarding address | 0b11)
  - **update reference** to forwarding address
- » target **not marked** yet
  - current **age** < tenuring threshold
    - copy object to “to” *Survivor* using 32k **PLAB** (-XX:YoungPLABSize=4096)
  - older or no space in *Young*
    - copy object to *Old* using 8k **PLAB** (-XX:OldPLABSize=1024)
  - **mark** previous object with **forwarding address** using CAS
    - failed – de-allocate back, read other thread updated forwarding address
    - success
      - for forwarding in *Young* update **age** of new object
      - DFS queuing of processing of object’s addresses of **old-to-young refs**
  - **update reference** to forwarding address

Note: all reference changes update card table iff address is in “to” *Survivor*

all PLAB or object re-allocations are **NUMA** aligned to speed-up collection

# Full Collector – Parallel Mark Compact

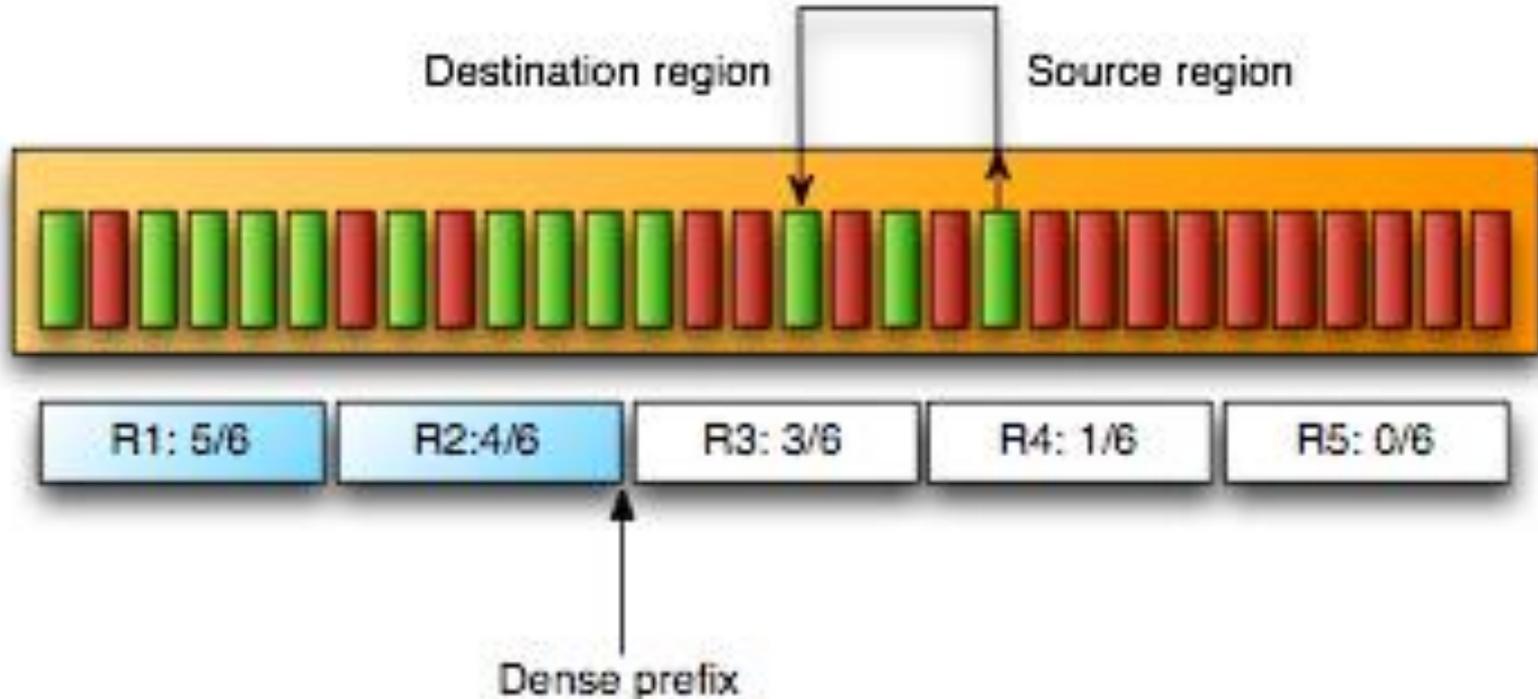
- » default for Oracle JVM 8
- » stop-the-world manner
- » multi-threaded
- » *Old* generation logically divided into fixed-size regions
- » uses **sliding compaction** - clean *Eden* and both *Survivors* as well
  - doesn't need additional memory, but is slower than copying
- » **parallel mark** phase
  - initiated with all roots (not using card table)
  - track all references (not just those pointing to *Young*)
  - info about reachable objects (location & size) is propagated to the corresponding region data



# Full Collector – Parallel Mark Compact

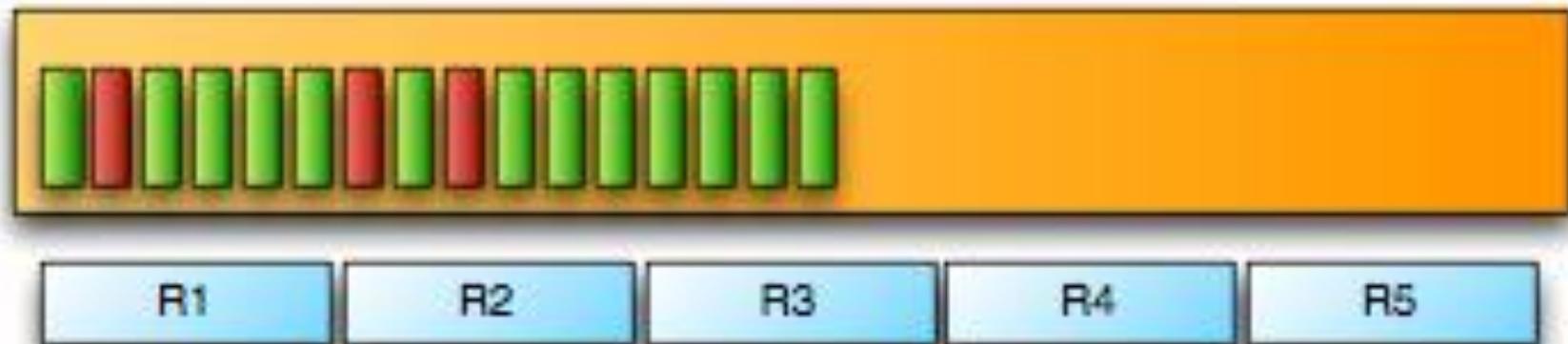
## » **serial summary** phase

- identify density of regions (due to previous compactions, older objects should be on the left, younger to right side)
- find from which region (starting from the left side) it has sense to do compaction based on recovered space from a region
  - *dense prefix* – left regions are not collected
- calculate new location of each live object; **most right regions will fill most left ones**; pretend data locality keeping their order



# Full Collector – Parallel Mark Compact

- » **parallel compaction/sweeping** phase
  - divide regions with some targets (start of objects)
  - each thread first compact the region itself and fill it by designated right regions
    - all references are updated based on summarized data (read only)
    - crossing map is updated to track the last object start in chunk
  - *no synchronization* needed, only one thread operate per each region
  - update root references and clean empty in parallel
  - finally, heap is packed, and large empty block is at the right end



# Full Collector – Parallel Mark Compact

- » support **strong generational hypothesis** – younger object dies earlier than older
  - objects with highest probability to survive are located on the left side of old generation (because of previous GC runs)
  - **dense prefix** completely *avoids their costly copying*
  - 50% of full collection work reclaim 82% of garbage
  - reclaim of additional 18% of garbage cost as much as previous work
- » dense prefix is adaptively updated
  - considering *used to total heap* ratio
  - affects pause time of full collection
- » after full collection
  - the whole *Young* is empty
  - the card table is cleaned (there are no references to *Young*)

- » **adaptive mechanism resizing** generations (-XX:+UseAdaptiveSizePolicy)
  - **max pause time** goal (-XX:MaxGCPauseMillis=<undef>)
    - if not met - shrink *Young* size
  - **throughput** goal (-XX:GCTimeRatio=99) – applied when the previous is met
    - if not met – increase *Young* and *Old* generations
      - *Young* increased according to its time portion in total time
  - **minimum footprint** goal – applied if all previous are met
    - shrink heap size

-XX:YoungGenerationSizeIncrement=20 ; -XX:TenuredGenerationSizeIncrement=20

-XX:AdaptiveSizeDecrementScaleFactor=4 (default 5%)

-XX:YoungGenerationSizeSupplement=80 (similar for tenured)

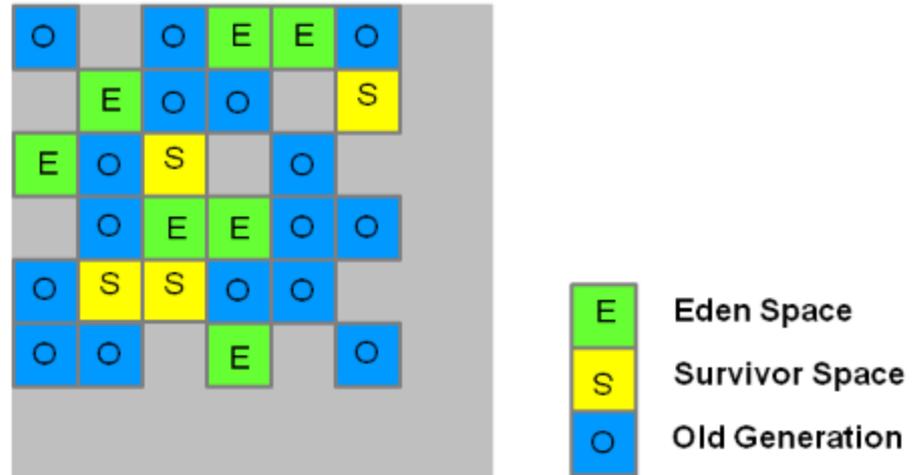
-XX:YoungGenerationSizeSupplementDecay=8 (8 times added)

-XX:TenuredGenerationSizeSupplementDecay=2 (2 times added)

# Garbage First (G1) Collector

- » **dynamic generational collector** called **G1GC** (-XX:+UseG1GC)
- » **concurrent** collector for large heaps (replacement for older CMS)
- » the whole heap is divided into **regions** (by def. to be close to 2048 regions 1-32MB)
- » no explicit separation between generations, only regions are mapped to generational spaces (generation is set of regions, changing in time)

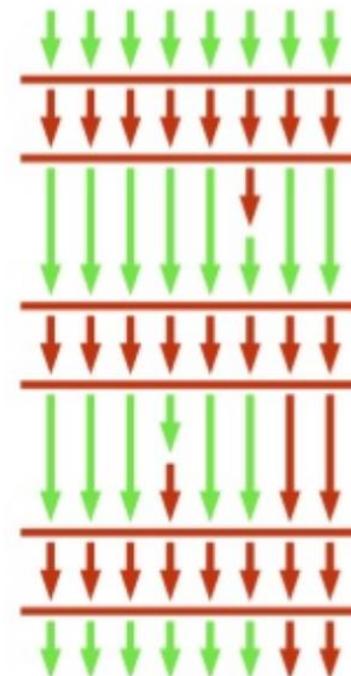
- » set of regions defines
  - » *Young* generation
  - » *Old* generation



- » compacting -> enables bump-the-pointer, TLABs, uses CAS
- » **copying** = copy live from a region to an empty region
- » keep **Humongous regions** (sequences) for objects  $\geq 50\%$  regions size
- » maintain list of free regions for constant time

# Garbage First (G1) Collector

- » **activities** in garbage first collector – **minor**, **mixed** and **full** collections
  - **parallel** with **global safe point** (stop the world)
    - initial marking pause – end of previous evacuation
    - final marking pause with data counting
      - prepare candidate regions for mixed
    - copying (evacuation)
  - **concurrent** with multiple threads
    - remember set refinement
    - marking + write barriers for concurrent modifications
    - clean-up
- » **major speed-up** is that **fast copying** approach is applied incrementally to *Old*
  - requires more heap than parallel due to concurrent activities
- » **controlled pause time** up to MaxGCPauseMillis
- » **poor handling of larger objects (humongous objects)**
- » **NUMA aware** – new Eden region from local memory
- » default since JVM 9



# Garbage First (G1) Collector – Remember Set

## » track references into a region

- ignore null and inter-region references
- old-to-young and old-to-old

» additional structures with ~5% heap overhead (max 20%)

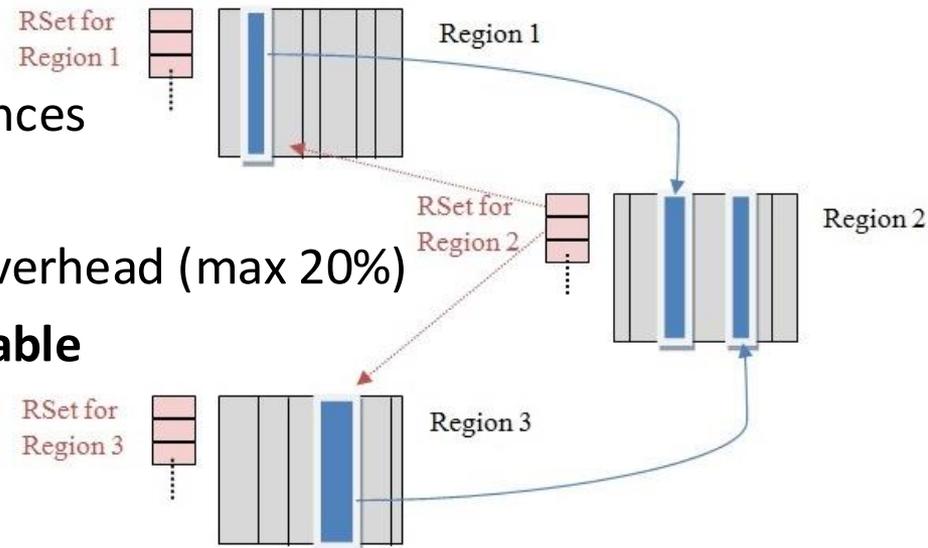
## » use **per-region-table** (PRT) with **card table**

updated *asynchronously* using  
*update thread log buffers*

- processed by refinement threads
- XX:G1ConcRefinementThreads=<n> (max threads)
- filled by *compiled write barrier* (pseudo code shown for simplification)

```
oop oldFooVal = this.foo;
if (GC.isMarking != 0 && oldFooVal != null){
    g1_wb_pre(oldFooVal);
}
this.foo = bar;
if ((this ^ bar) >> 20) != 0 && bar != null) {
    g1_wb_post(this);
}
```

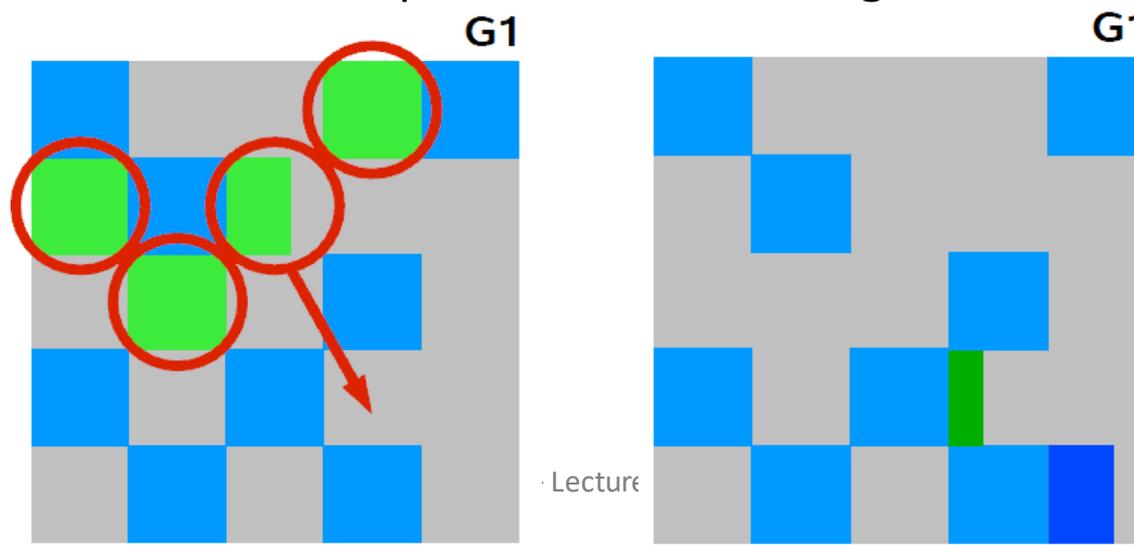
log<sub>2</sub> of region size (1MB)



-XX:+G1SummarizeRSetStats -XX:G1SummarizeRSetStatsPeriod=1

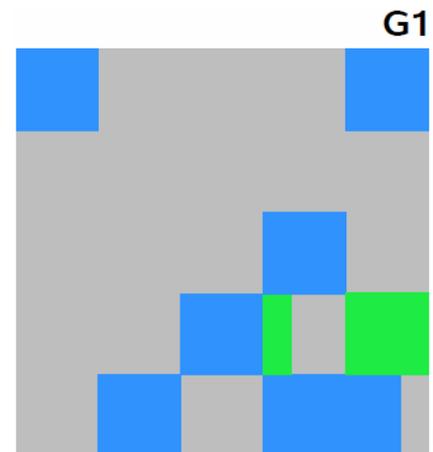
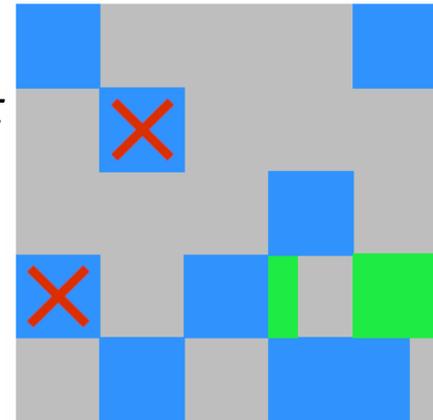
# Garbage First (G1) Collector – Minor and Mixed Collection

- » stop-the-world approach with **parallel threads**
- » **triggered** when no more allocation in *Young* regions possible
- » **collection set** (CSet)
  - *Eden* and “from” *Survivor* regions for pure **minor** collection
  - *Eden*, “from” *Survivor* and *candidate Old regions* for **mixed** collection
- » reachable objects identified from roots + RSet for the regions + card table
- » reachable objects are copied (from *Eden* and *Survivor* regions) into one or more new *Survivor* regions
  - using forwarding address with marking like parallel scavenge
- » if aging threshold is met => promoted into *Old* regions



# Garbage First (G1) Collector – Marking Phase

- » **triggered by** heap occupancy percent (-XX:InitiatingHeapOccupancyPercent=45)
- » outcomes
  - **candidate *Old* regions** with a lot of garbage for mixed collection
  - cleanup completely empty *Old* regions
- » **initial mark** – done after minor collection *utilizing global safe point (GSP)*
  - snapshot-at-the-beginning (SATB) – scan roots
- » **marking and region-based statistics collection** – *concurrent*  
(-XX:ConcGCThreads=<n>)
  - can be interrupted by minor GC
  - pre-write barrier keeps previous reference in SATB
- » **final mark** - right after the next minor collection *in GSP*
  - reflect changes in previous minor collections and allocations utilizing modifications in card tables
  - summarize and prepare ordered candidates



# Garbage First (G1) Collector – Full Collection

- » multiphase **full tracking with compact of all regions** during global safe point
- » triggered by
  - **concurrent mode failure** – *Old* fill-up before concurrent marking is complete
    - increase heap, decrease trigger threshold, more concurrent threads
  - **promotion failure** – mixed collection runs-out of space in *Old*
    - trigger sooner
  - **evacuation failure** – minor collection has no more space for promotion
    - increase heap
  - **humongous allocation failure** – no space for large objects
    - avoid large objects (>50% of region size)
    - increase region size (alternatively increase heap)
      - max region size is 32MB

# Garbage First (G1) Collector – Humongous Objects

- » objects larger than  $\frac{1}{2}$  of the region are considered as **humongous**
  - with 1MB region it is just 500kB -> there can be a lot of such objects
- » **allocation**
  - check concurrent trigger and optionally start concurrent marking
  - one set of humongous regions contain just one such object
    - **waste** up to region size – 1 + allocated **out of Young** generation
  - not having sequence of free regions for allocation of an object trigger **expensive full collection**
- » **reclamation** of non-reachable humongous objects during
  - cleanup phase of concurrent cycle
  - full collection (can compact free space)
- » **debug** humongous allocations
  - `-XX:+UnlockExperimentalVMOptions -XX:G1LogLevel=finest -XX:+PrintAdaptiveSizePolicy`
  - use **Java Flight Recorder** in Java Mission Control
    - all allocations tracked in runtime like TLAB allocations

# Garbage First (G1) Collection – Tuning Options 😊

|                                          |                                |                                        |
|------------------------------------------|--------------------------------|----------------------------------------|
| G1ConcMarkForceOverflow                  | G1HRRSFlushLogBuffersOnVerify  | G1SATBBufferEnqueueingThresholdPercent |
| G1ConcMarkStepDurationMillis             | G1HRRSUseSparseTable           | G1SATBBufferSize                       |
| G1ConcRSHotCardLimit                     | G1HeapRegionSize               | G1SATBProcessCompletedThreshold        |
| G1ConcRSLogCacheSize                     | G1HeapWastePercent             | G1ScrubRemSets                         |
| G1ConcRefinementGreenZone                | G1MarkingOverheadPercent       | G1SecondaryFreeListAppendLength        |
| G1ConcRefinementRedZone                  | G1MarkingVerboseLevel          | G1StressConcRegionFreeing              |
| G1ConcRefinementServiceIntervalMillis    | G1MaxVerifyFailures            | G1StressConcRegionFreeingDelayMillis   |
| G1ConcRefinementThreads                  | G1MixedGCCountTarget           | G1SummarizeConcMark                    |
| G1ConcRefinementThresholdStep            | G1PrintHeapRegions             | G1SummarizeRSetStats                   |
| G1ConcRefinementYellowZone               | G1PrintRegionLivenessInfo      | G1SummarizeRSetStatsPeriod             |
| G1ConcRegionFreeingVerbose               | G1RSBarrierRegionFilter        | G1TraceConcRefinement                  |
| G1ConfidencePercent                      | G1RSScrubVerbose               | G1TraceHeapRegionRememberedSet         |
| G1DummyRegionsPerGC                      | G1RSetRegionEntries            | G1TraceMarkStackOverflow               |
| G1EvacuationFailureALot                  | G1RSetRegionEntriesBase        | G1UpdateBufferSize                     |
| G1EvacuationFailureALotCount             | G1RSetScanBlockSize            | G1UseAdaptiveConcRefinement            |
| G1EvacuationFailureALotDuringConcMark    | G1RSetSparseRegionEntries      | G1VerifyBitmaps                        |
| G1EvacuationFailureALotDuringInitialMark | G1RSetSparseRegionEntriesBase  | G1VerifyCTCleanup                      |
| G1EvacuationFailureALotDuringMixedGC     | G1RSetUpdatingPauseTimePercent | G1VerifyHeapRegionCodeRoots            |
| G1EvacuationFailureALotDuringYoungGC     | G1RecordHRRSEvents             | G1VerifyRSetsDuringFullGC              |
| G1EvacuationFailureALotInterval          | G1RecordHRRSOops               | G1YoungSurvRateNumRegionsSummary       |
| G1ExitOnExpansionFailure                 | G1RefProcDrainInterval         | G1YoungSurvRateVerbose                 |
| G1FailOnFPError                          | G1ReservePercent               | PrintCFG1                              |