Microsoft

jax LONDON

Java Team

OpenJDK: In the New Age of Concurrent Garbage Collectors

HotSpot's Regionalized GCs

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Agenda

Part 1 – Groundwork & Commonalities

Laying the Groundwork

Stop-the-world (STW) vs concurrent collection

Heap layout – regions and generations

Basic Commonalities

Copying collector – from and to spaces

Regions – occupied and free

Collection set and priority

Oct 8th, 2019

Agenda

Part 2 – Introduction & Differences

Introduction to G1, Shenandoah and Z GCs

Algorithm

Basic Differences

GC phases

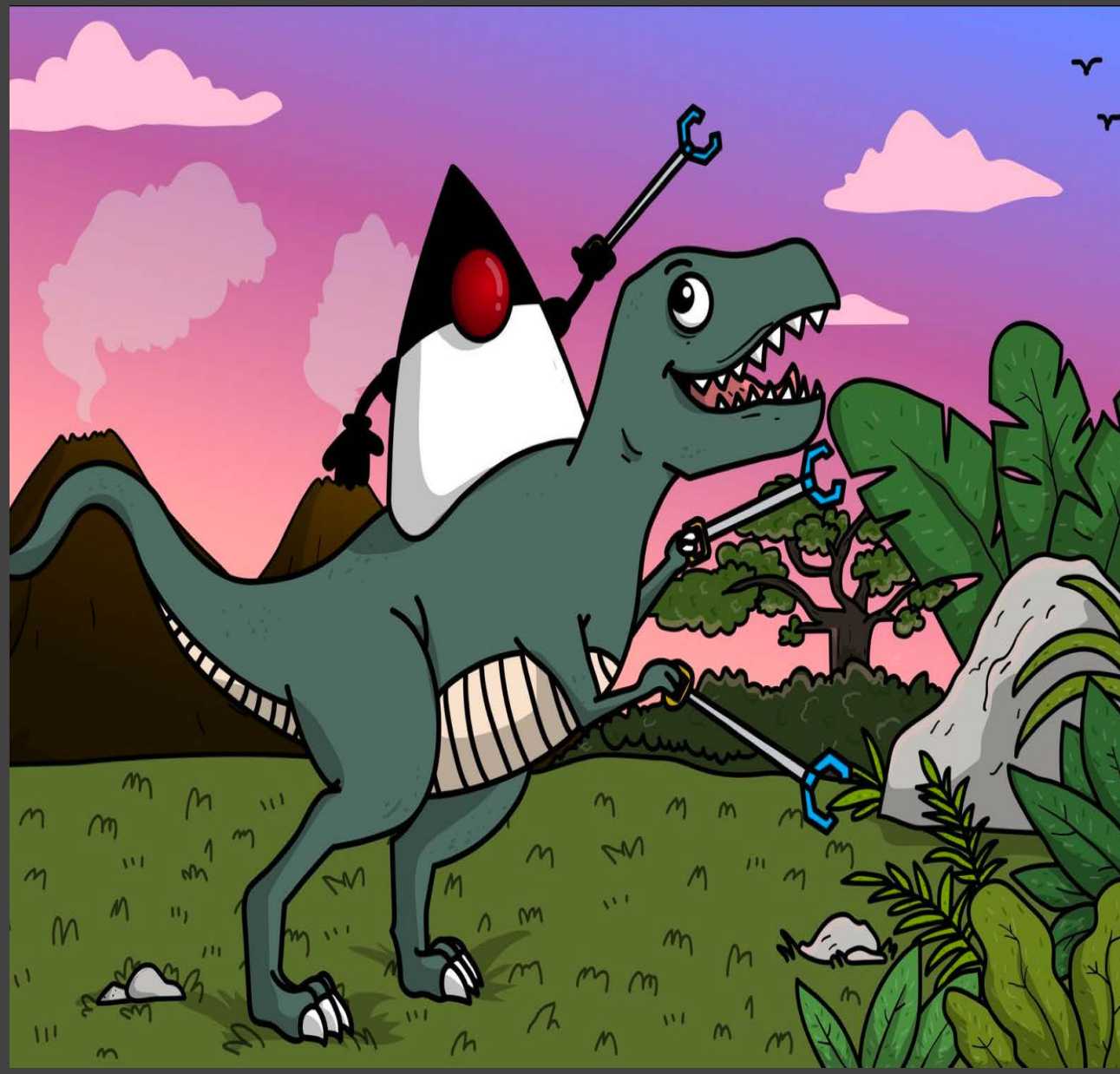
Marking

Barriers

Compaction

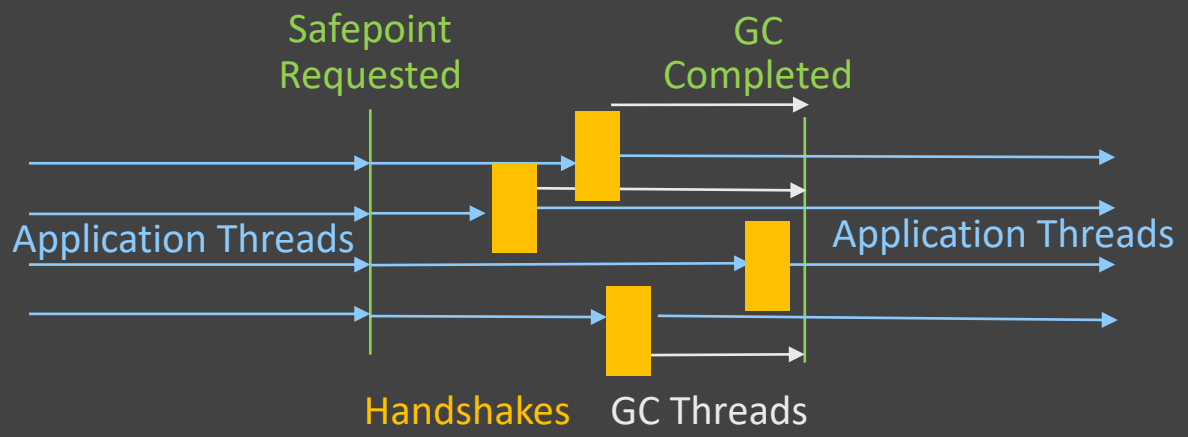
Oct 8th, 2019

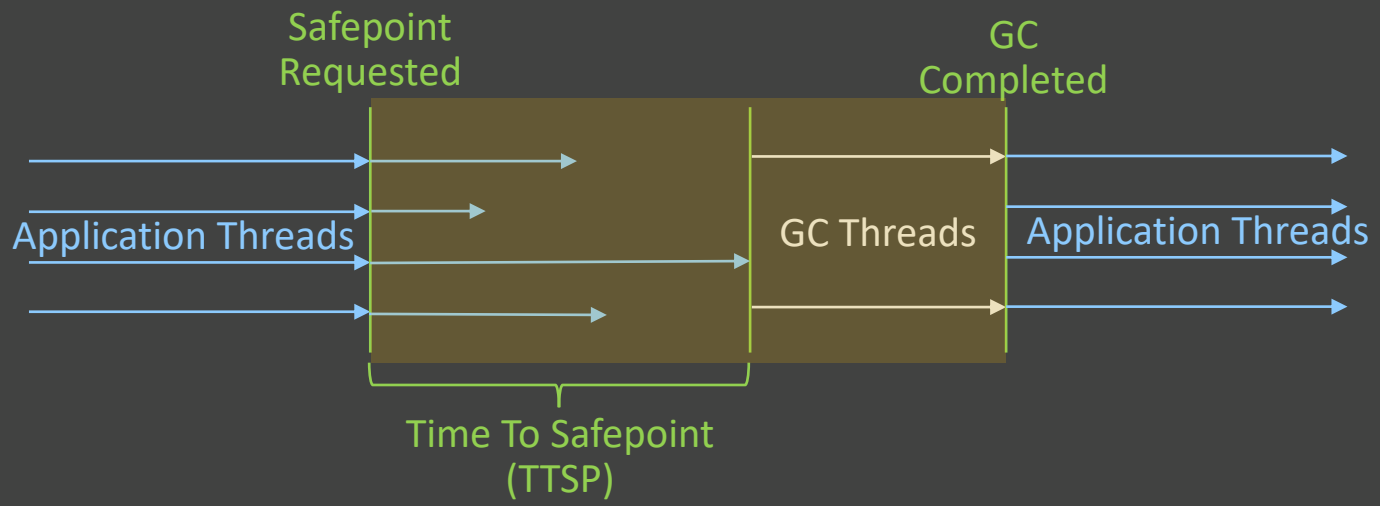
Groundwork : Stop-the world vs concurrent collections



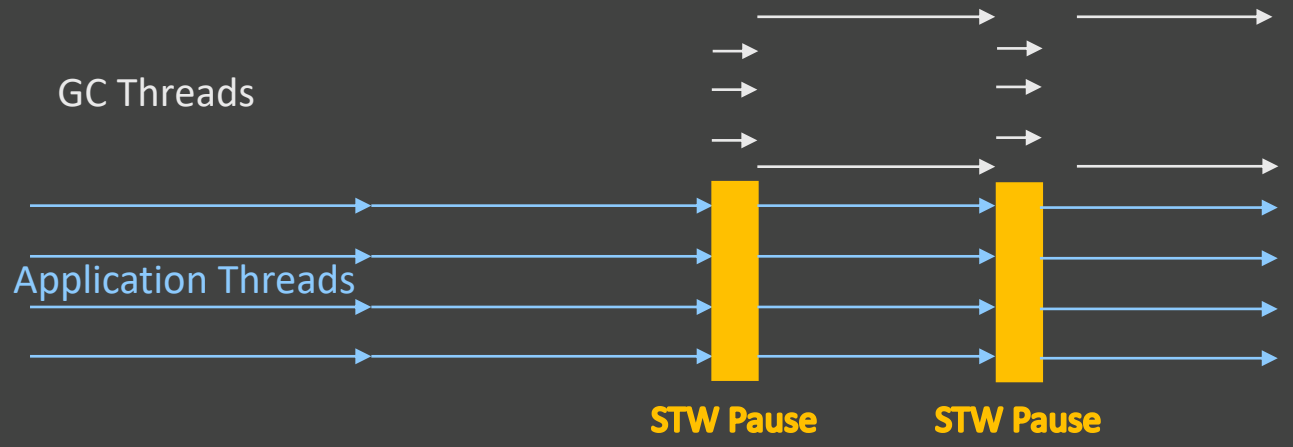
Stop-the-world aka STW GC

Thread local handshakes vs Global

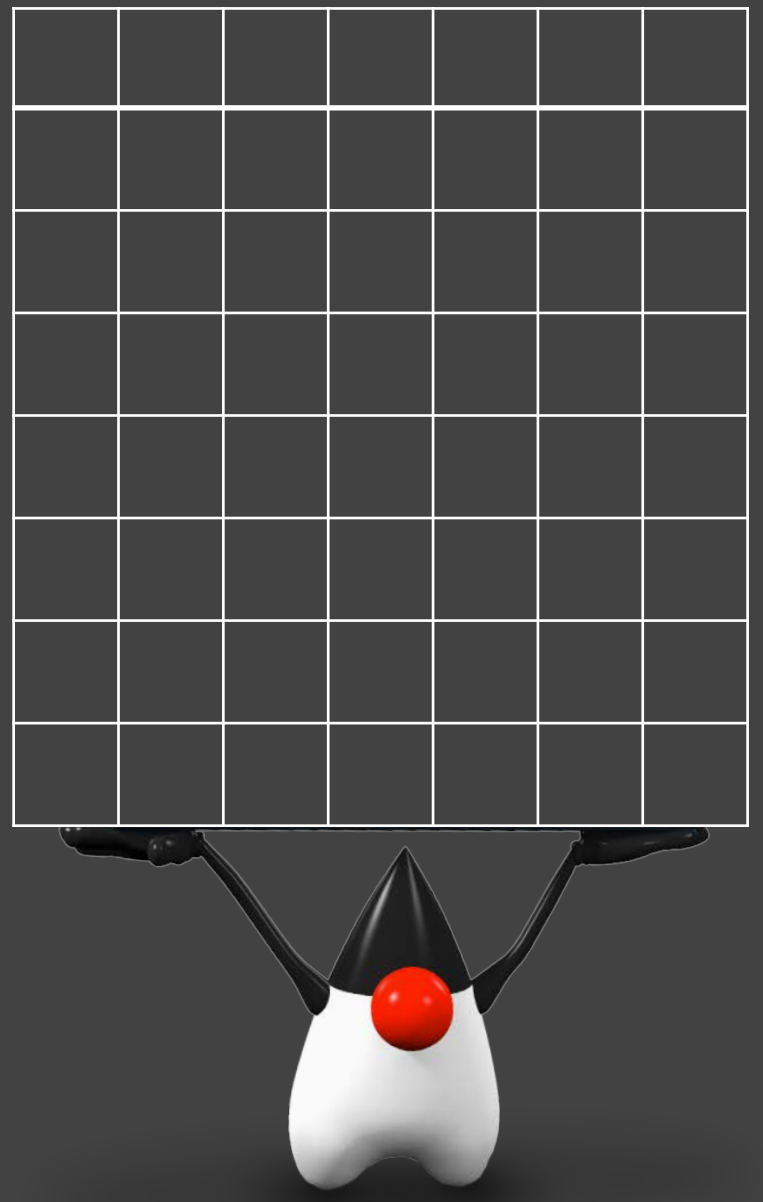




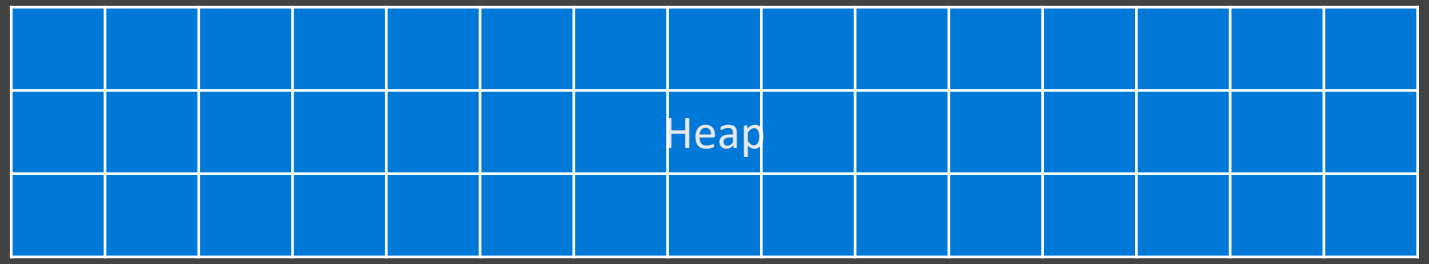
Concurrent GC



Groundwork : Heap layout - regions and generations

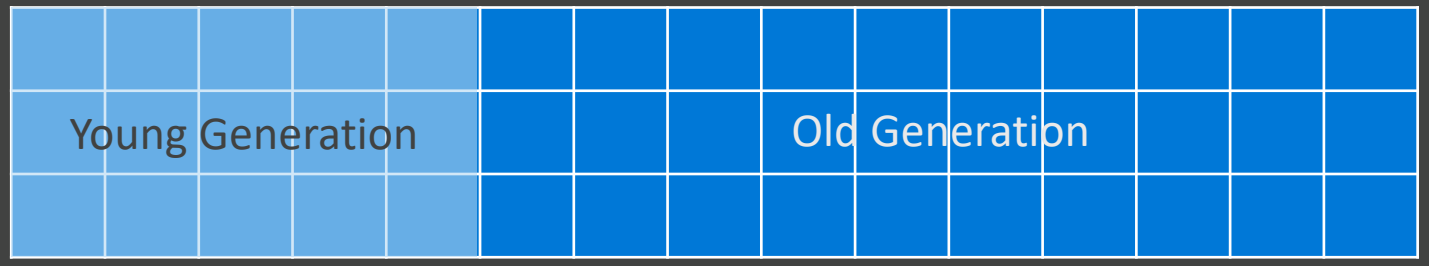


Heap Layout



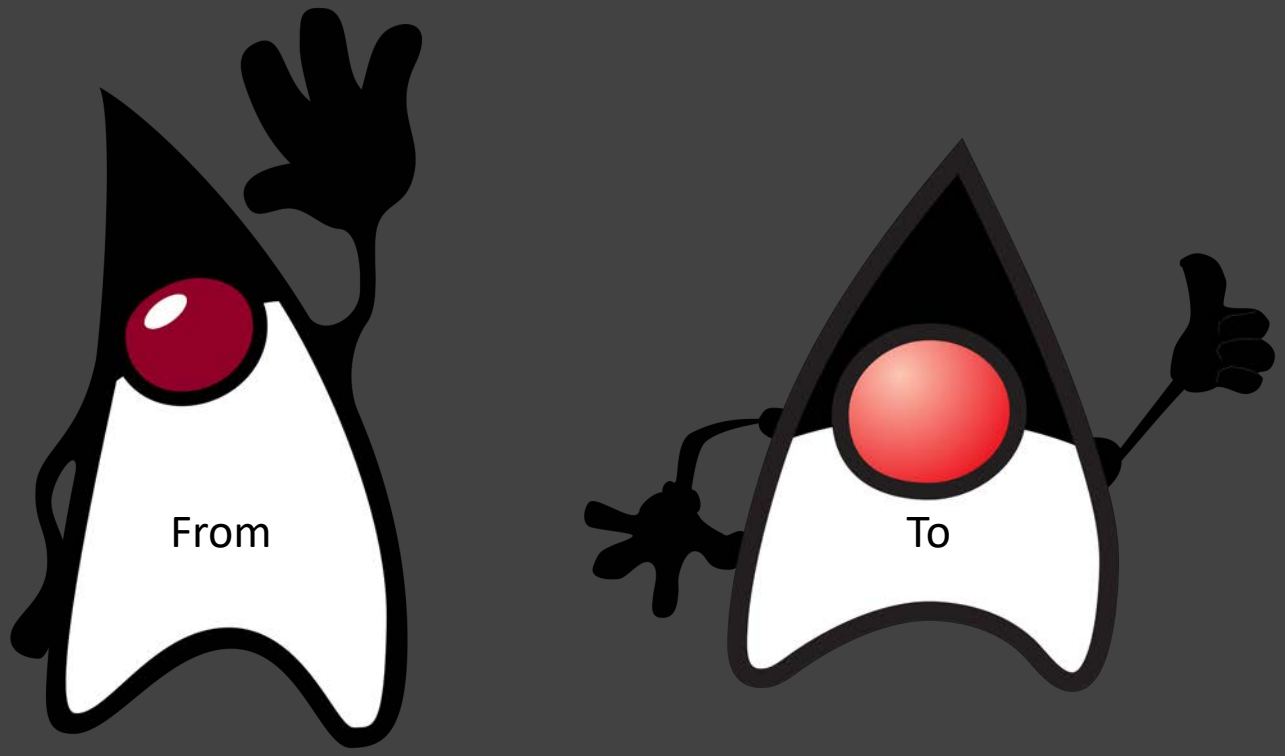
Z GC

Shenandoah GC



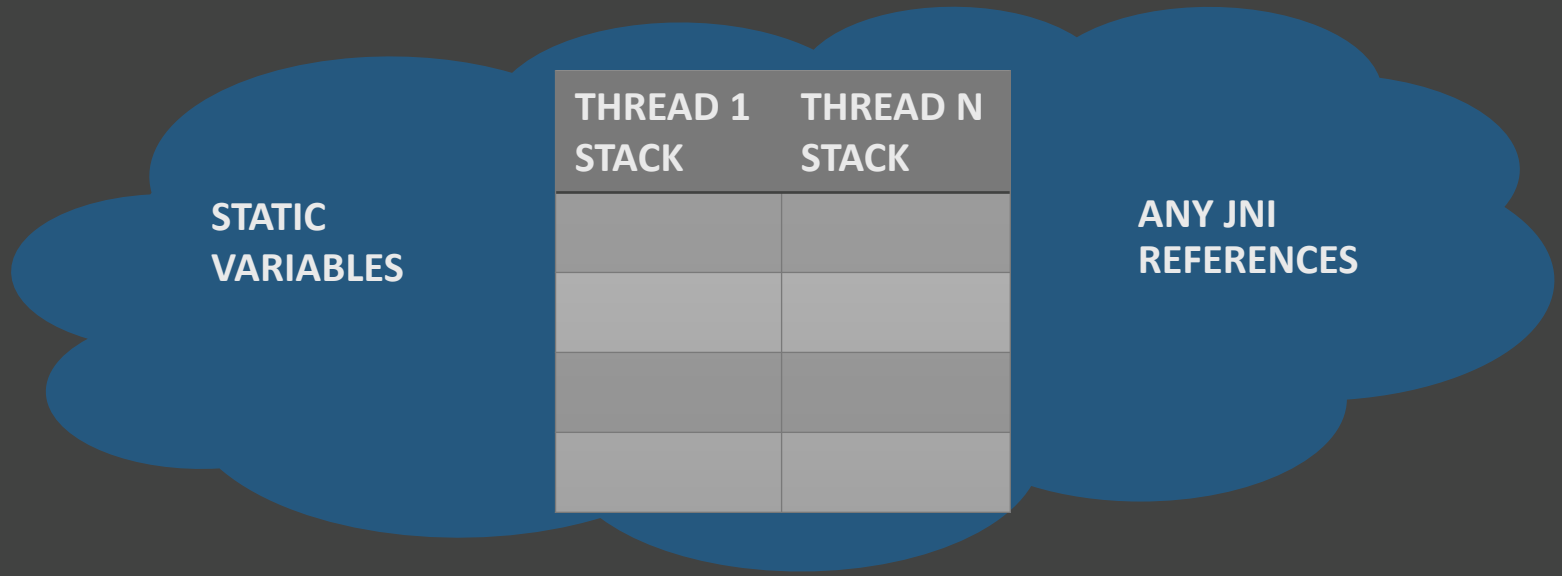
G1 GC

Commonalities : Copying collector – from and to spaces

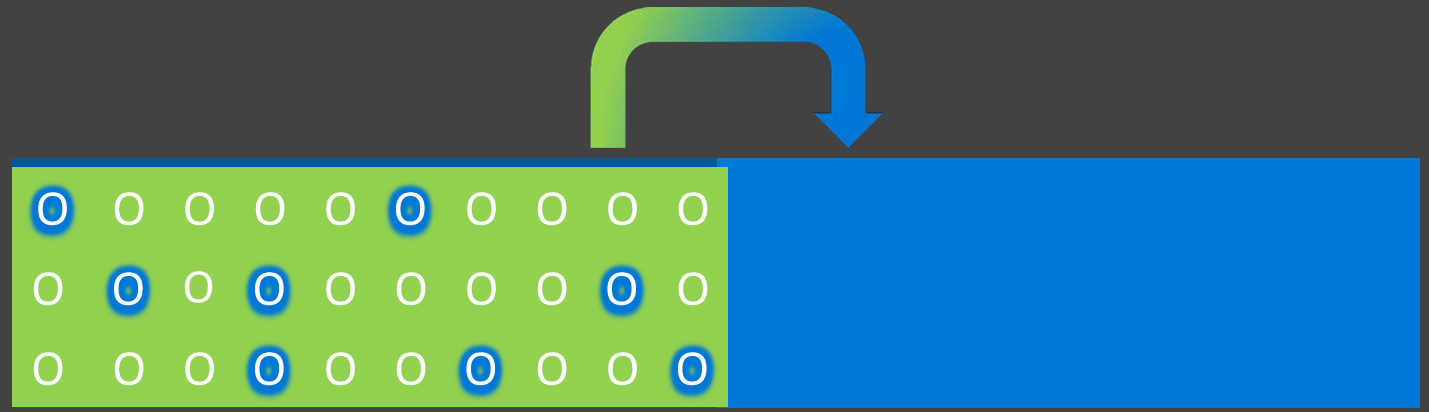


Copying Collector aka Compacting Collector aka Evacuation

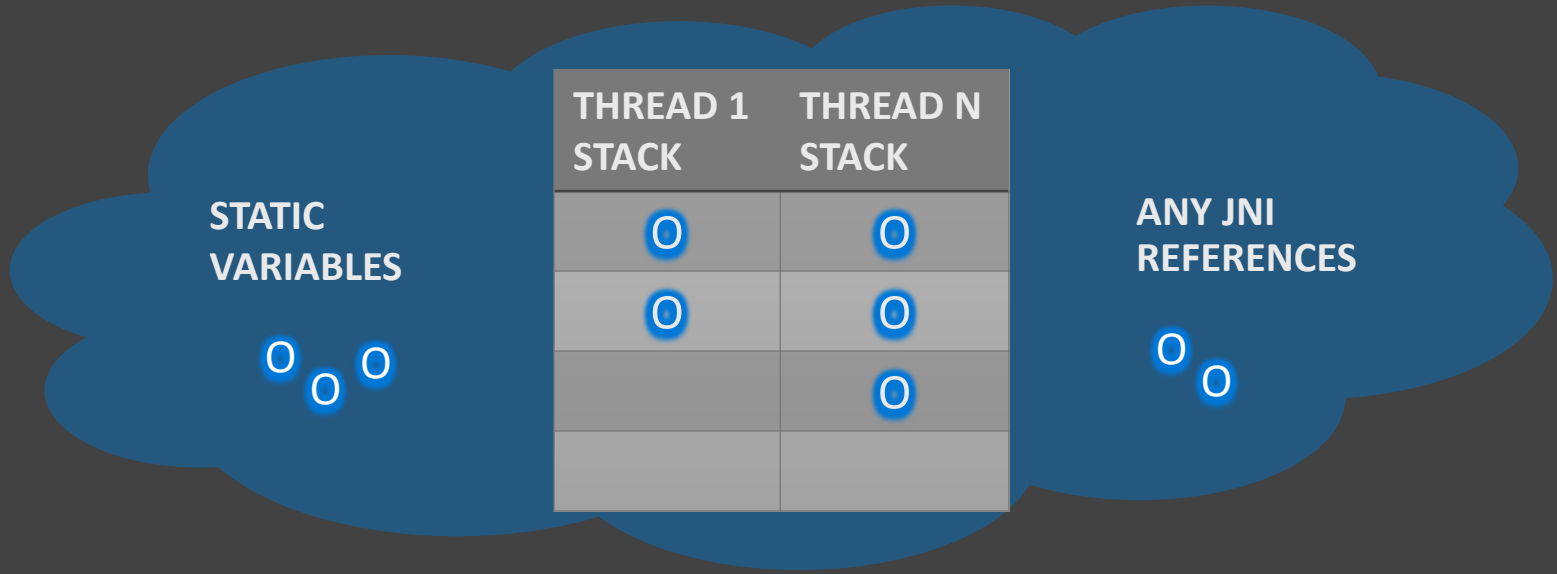
GC ROOTS



Copying Collector aka Compacting Collector aka Evacuation



GC ROOTS



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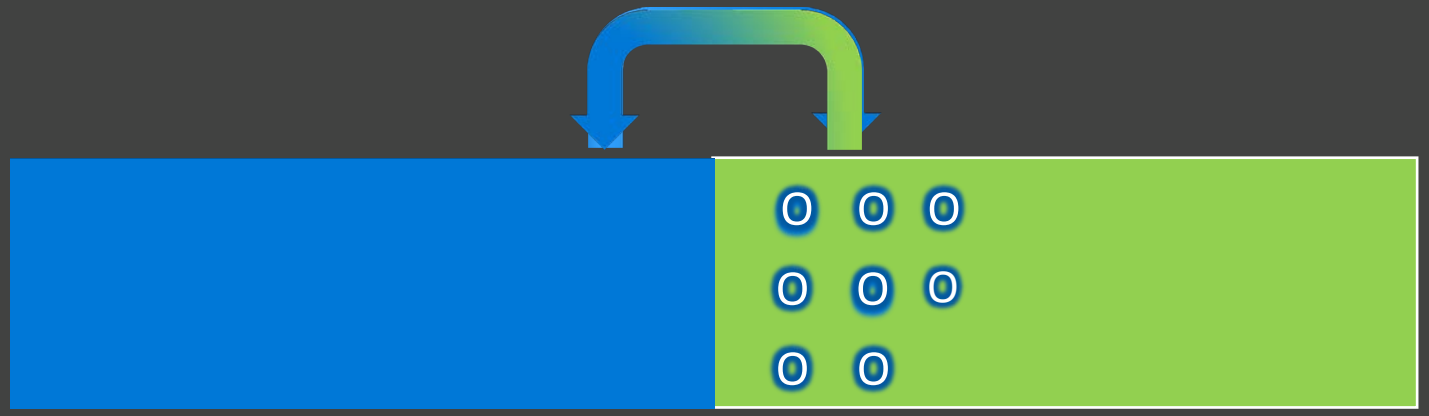
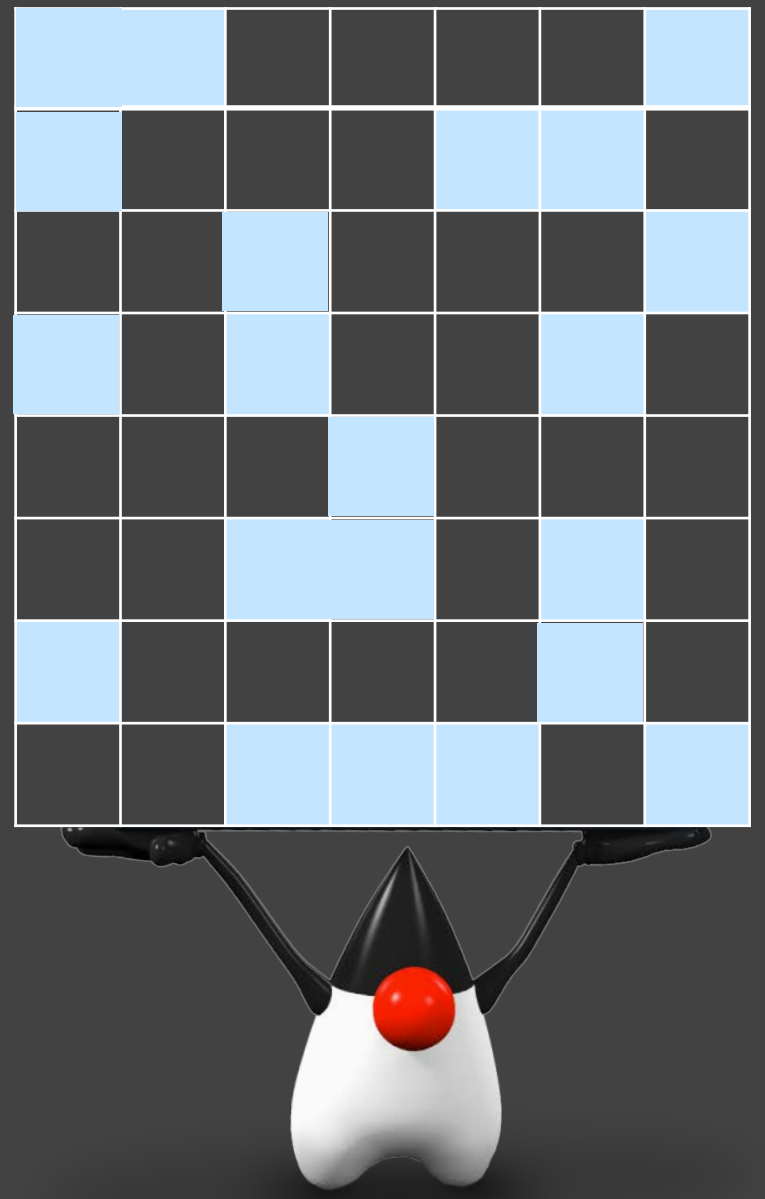
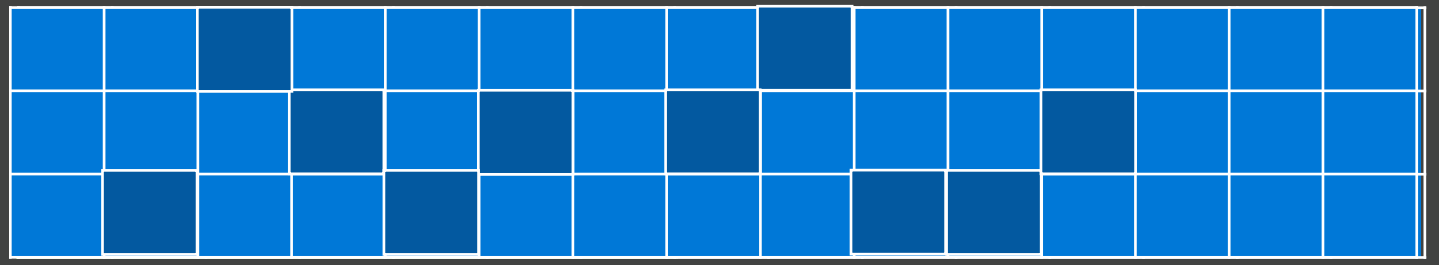


Commonalities : Regions – occupied and free

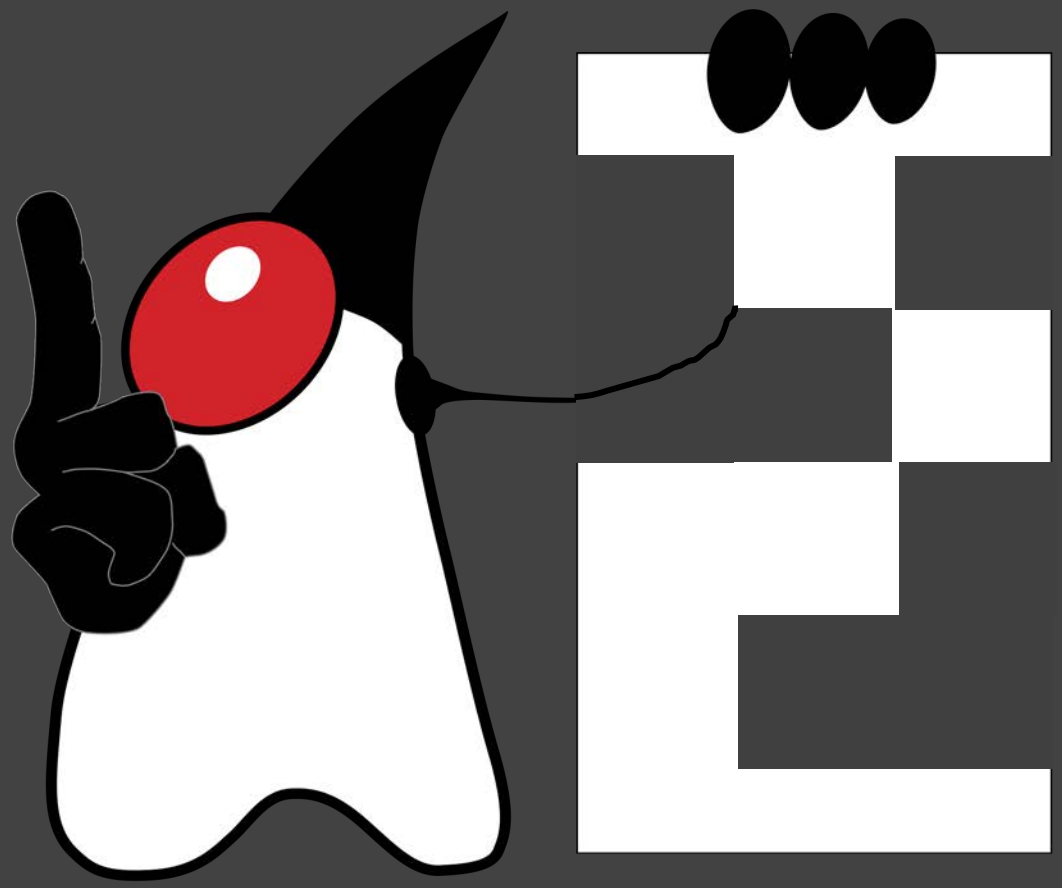


Occupied and Free Regions

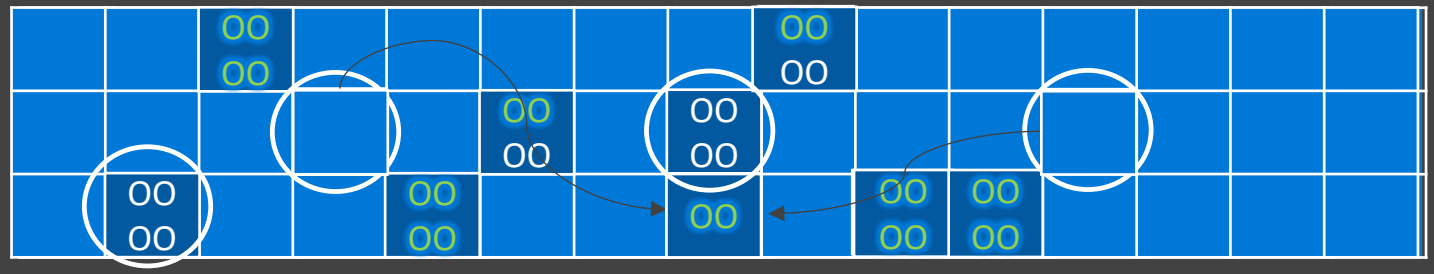


- List of free regions
- In case of generational heap (like G1), the occupied regions could be young, old or humongous

Commonalities : Collection set and priority

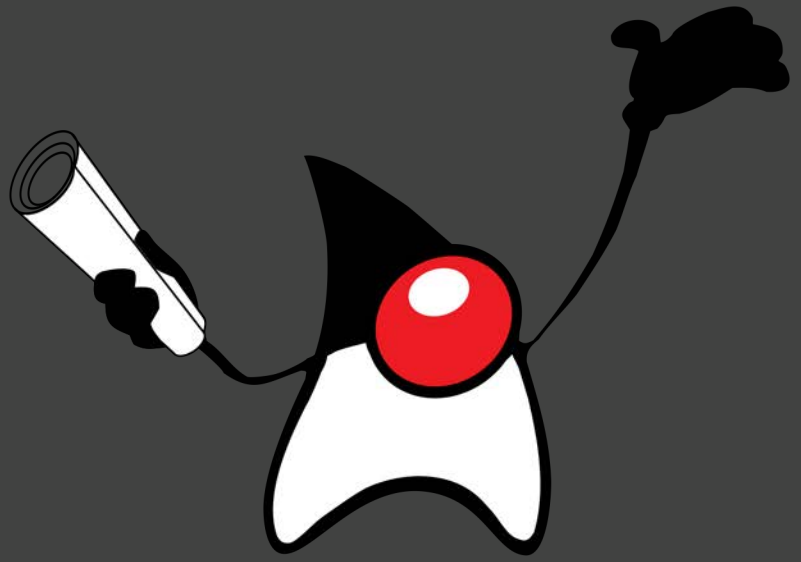


Collection Priority and Collection Set



- Priority is to reclaim regions with most garbage
- The candidate regions for collection/reclamation/relocation are said to be in a collection set
  - There are threshold based on how expensive a region can get and maximum regions to collect
- Incremental collection aka incremental compaction or partial compaction
  - Usually needs a threshold that triggers the compaction
  - Stops after the desired reclamation threshold or free-ness threshold is reached
  - Doesn’t need to be stop-the-world

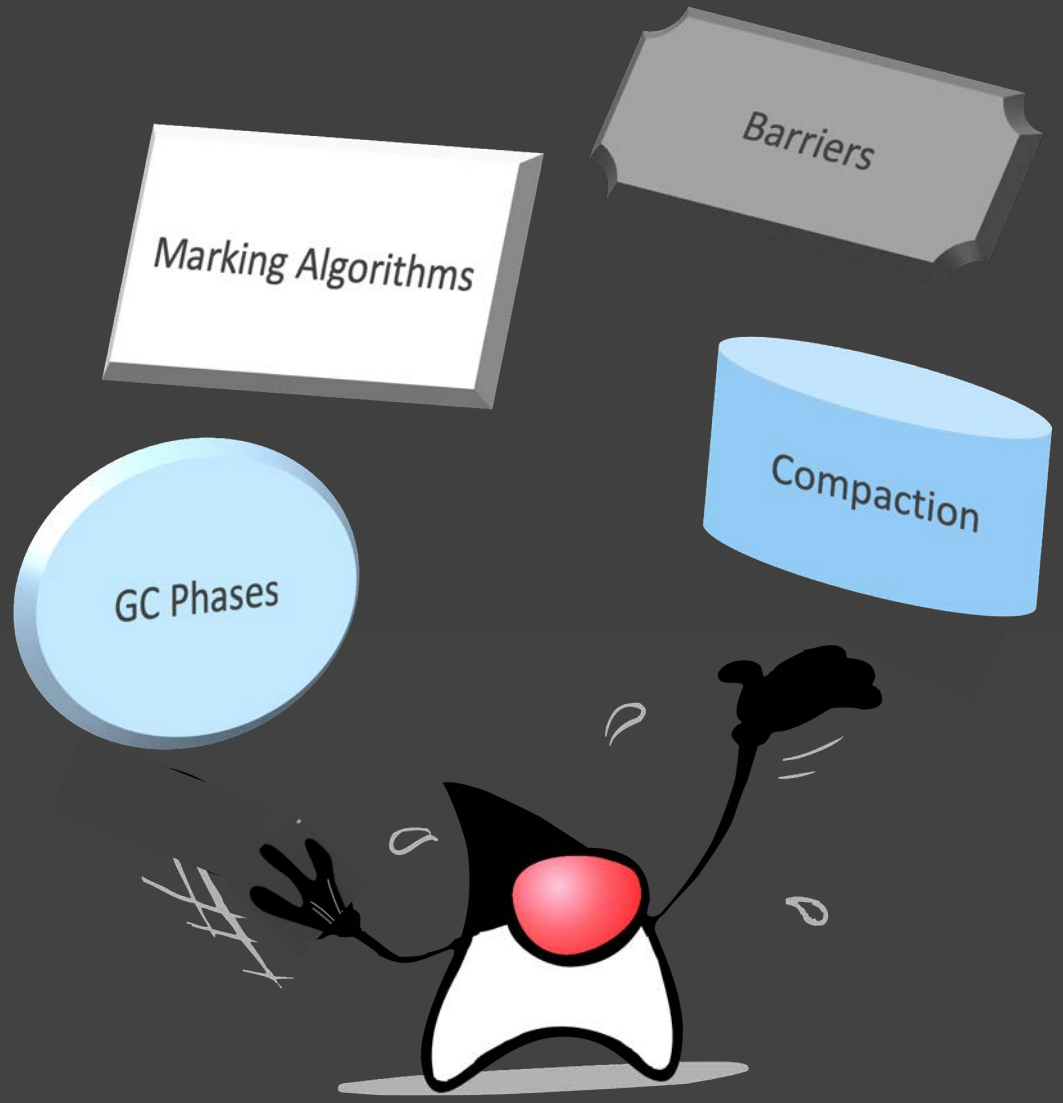
Introduction : G1, Shenandoah & Z - Algorithms



Algorithm and Other Considerations

Garbage Collectors
Regionalized?
Generational?
Compaction?
Target Pause Times?
Concurrent Marking Algorithm?

Differences – G1



GC Phases of Marking and Compaction

G1 GC	Gist
Initial Mark	Mark objects directly reachable by the roots
Concurrent Root Region Scanning	Since initial mark is piggy-backed on a young collection, the survivor regions need to be scanned
Concurrent Marking	Snapshot-at-the-beginning (SATB) algorithm
Final Marking	Drain SATB buffers; traverse unvisited live objects
Cleanup	Identify and free completely free regions, sort regions based on liveness and expense
STW Compaction	Move objects in collection set to “to” regions; free regions in collection set

•C. Hunt, M. Beckwith, P. Parhar, B. Rutisson. Java Performance Companion.

Concurrent Marking

Snapshot-at-the-beginning (SATB) Algorithm

Logical snapshot of the heap

SATB marking guarantees that all garbage objects that are present at the start of the concurrent marking phase will be identified by the snapshot

But, application mutates its object graph

- Any new objects are considered live
- For any reference update, the mutator needs to log the previous value in a log queue
  - This is enabled by a pre-write barrier

- C. Hunt, M. Beckwith, P. Parhar, B. Rutisson. Java Performance Companion.
- https://www.jfokus.se/jfokus17/preso/Write-Barriers-in-Garbage-First-Garbage-Collector.pdf

Barriers

SATB Pre-Write Barrier

The pseudo-code of the pre-write barrier for an assignment of the form x.f := y is:

```
if (marking_is_active) {
      pre_val := x.f;
      if (pre_val != NULL) {
            satb_enqueue(pre_val);
      }
}
```

- C. Hunt, M. Beckwith, P. Parhar, B. Rutisson. Java Performance Companion.

Barriers

Post Write Barrier

Consider the following assignment:

```
object.field = some_other_object
```

G1 GC will issue a write barrier after the reference is updated, hence the name.

G1 GC filters the need for a barrier by way of a simple check as explained below:

```
(&object.field XOR &some_other_object) >> RegionSize
```

If the check evaluates to zero, a barrier is not needed.

If the check != zero, G1 GC enqueues the card in the update log buffer

https://www.jfokus.se/jfokus17/preso/Write-Barriers-in-Garbage-First-Garbage-Collector.pdf

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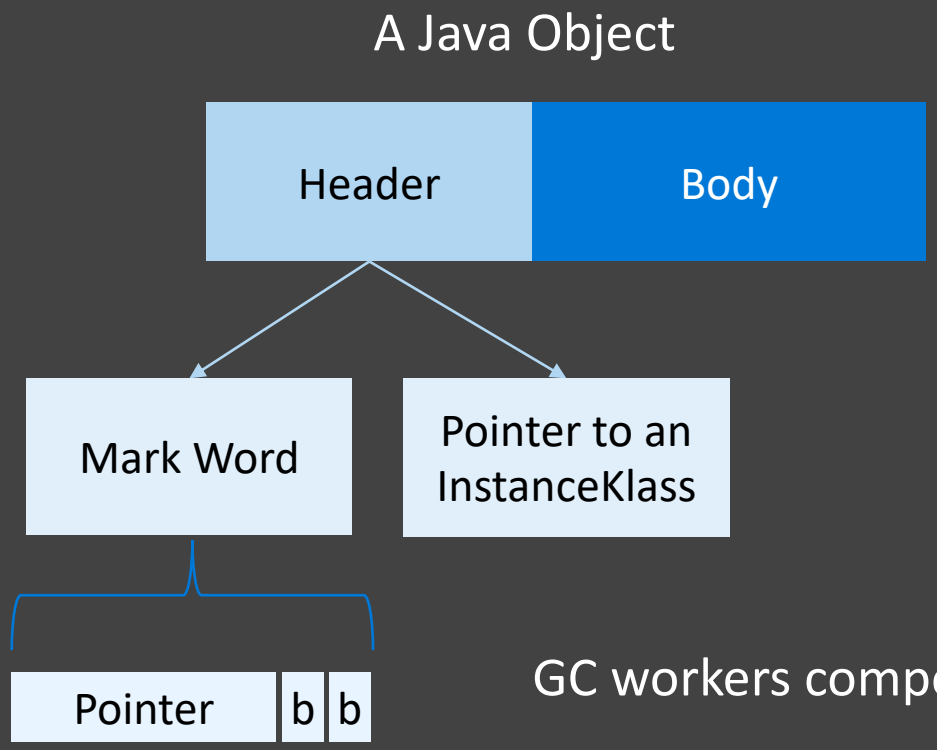
STW Compaction

Forwarding Pointer in Header

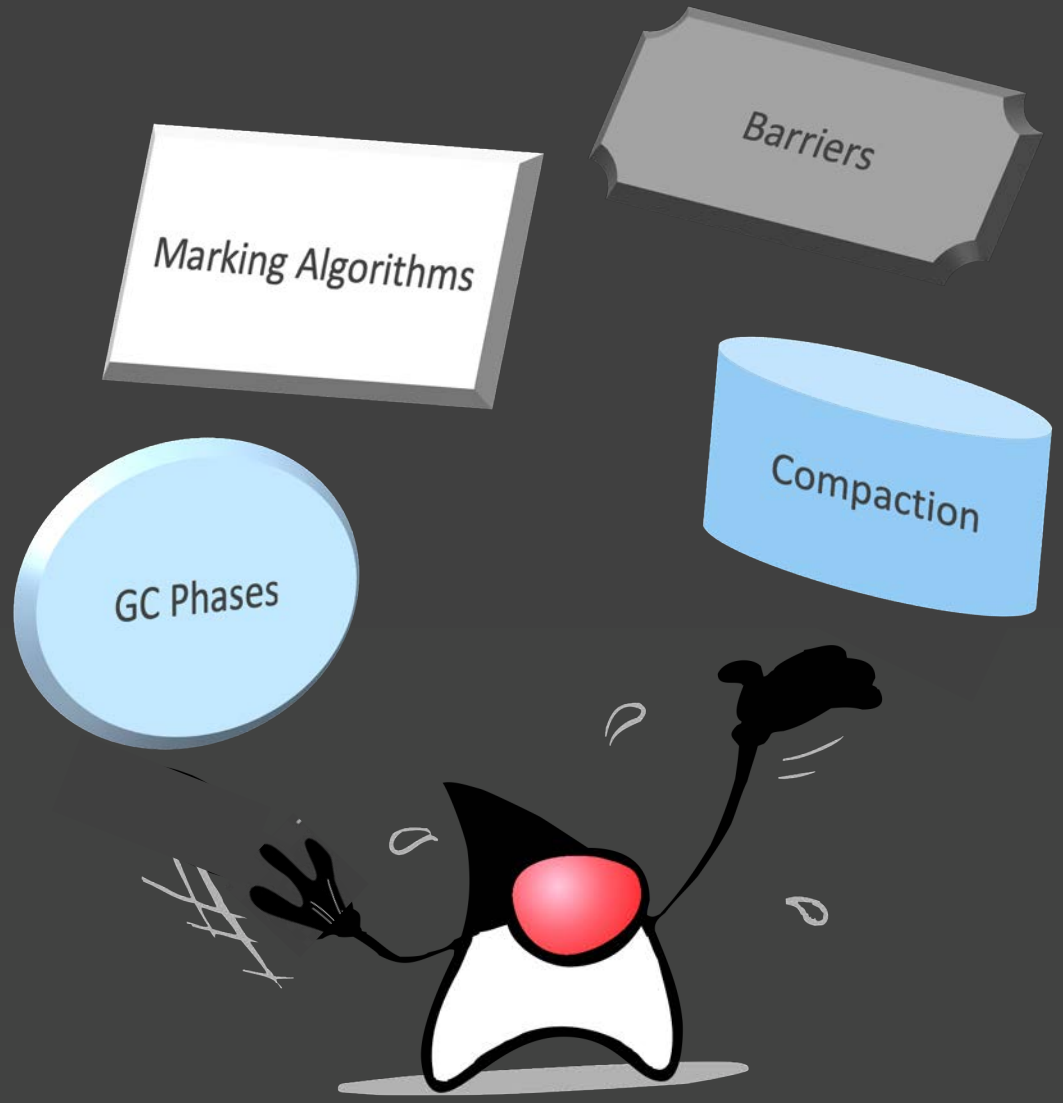


GC workers compete to install the forwarding pointer

From source:

- An InstanceKlass is the VM level representation of a Java class. It contains all information needed for at class at execution runtime.
- When marked the bits will be 11

Differences – Z



GC Phases of Marking and Compaction

Z GC	Gist
Initial Mark	Mark objects directly reachable by the roots
Concurrent Marking	Striping - GC threads walk the object graph and mark
Final Marking	Traverse unvisited live objects; weak root cleaning
Concurrent Prepare for Compaction	Identify collection set; reference processing
Start Compaction	*Handles roots into the collection set*
Concurrent Compaction	Move objects in collection set to “to” regions
Concurrent Remap (done with Concurrent Marking of next cycle since walks the object graph)	Fixup of all the pointers to now-moved objects

http://cr.openjdk.java.net/~pliden/slides/ZGC-Jfokus-2018.pdf

Concurrent Marking

Colored Pointers

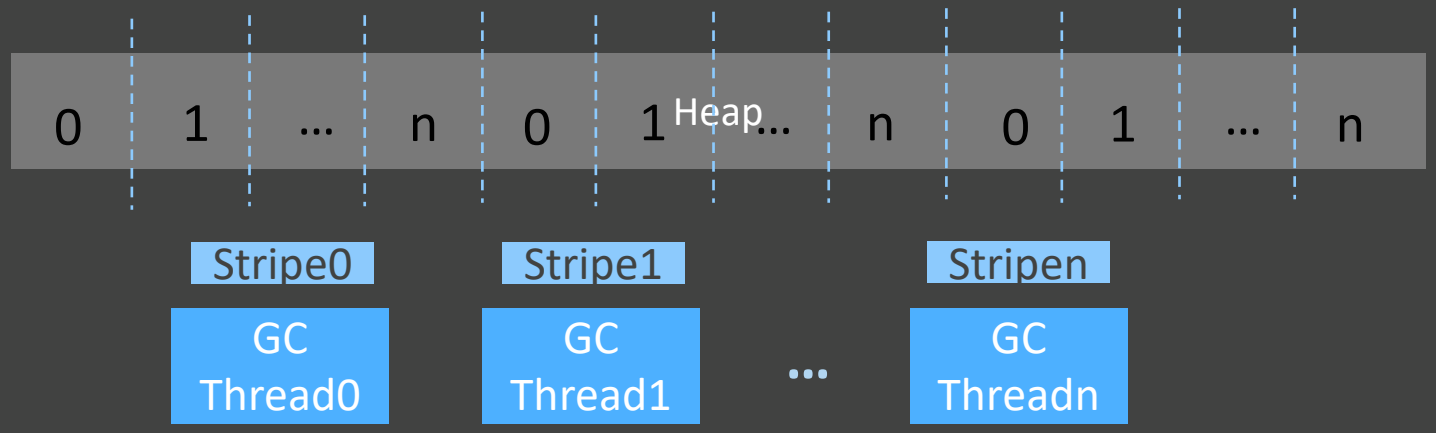
Heap divided into logical stripes

- GC threads work on their own stripe
- Minimizes shared state

Load barrier to detect loads of non-marked object pointers

Concurrent reference processing

Thread local handshakes



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Barriers

Loaded Reference Barrier

Update a “bad” reference to a “good” reference
Can be self-healing/repairing barrier when updates the source memory location
Imposes a set of invariants –

“All visible loaded reference values will be safely “marked through” by the collector, if they haven’t been already.
All visible loaded reference values point to the current location of the safely accessible contents of the target objects they refer to.”

Tene, G.; Iyengar, B. & Wolf, M. (2011), C4: The Continuously Concurrent Compacting Collector, *in* 'Proceedings of the international symposium on Memory management' , ACM, New York, NY, USA , pp. 79--88 .

Example

Object o = obj.fieldA; // Loading an object reference from heap

load_barrier(register_for(o), address_of(obj.fieldA));

```
if (o & bad_bit_mask) {
slow_path(register_for(o),
address_of(obj.fieldA)); }
```

Example

```
mov 0x20(%rax), %rbx     // Object o = obj.fieldA;
test %rbx, (0x16)%r15     // Bad color?
jnz slow_path             // Yes -> Enter slow path and mark/relocate/remap,
                          // adjust 0x20(%rax) and %rbx
```

http://cr.openjdk.java.net/~pliden/slides/ZGC-Jfokus-2018.pdf

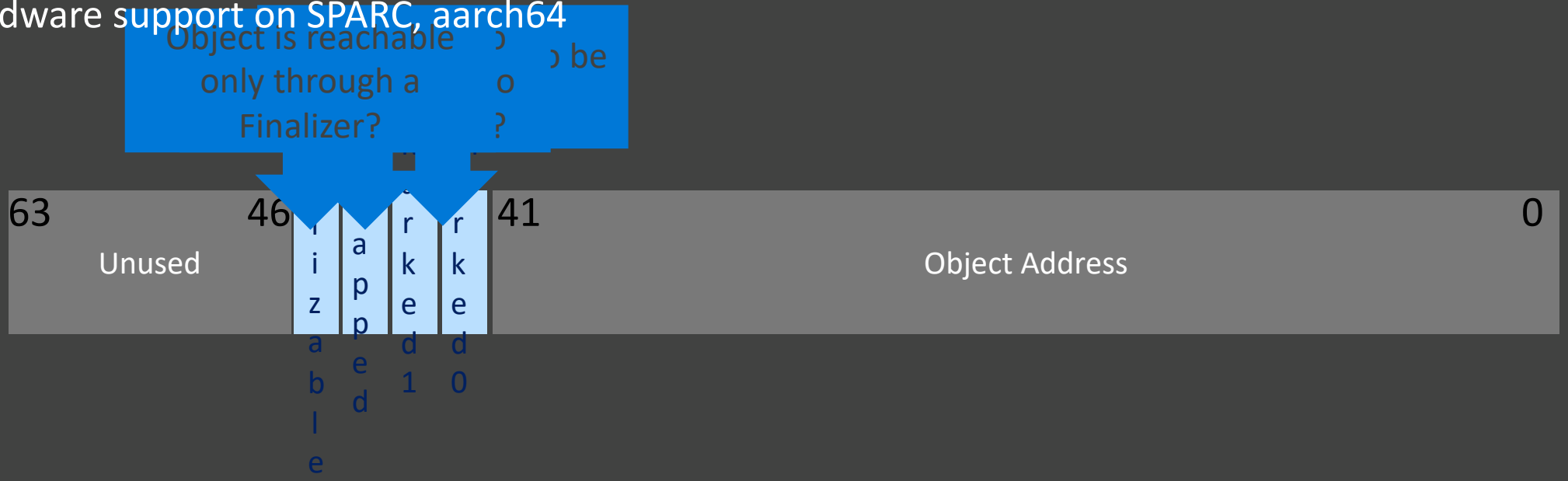
Core Concept

Colored Pointers

Metadata stores in the unused bits of the 64 bit pointers

Virtual address mapping/tagging

- Multi-mapping on x86-64
- Hardware support on SPARC, aarch64



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Concurrent Compaction

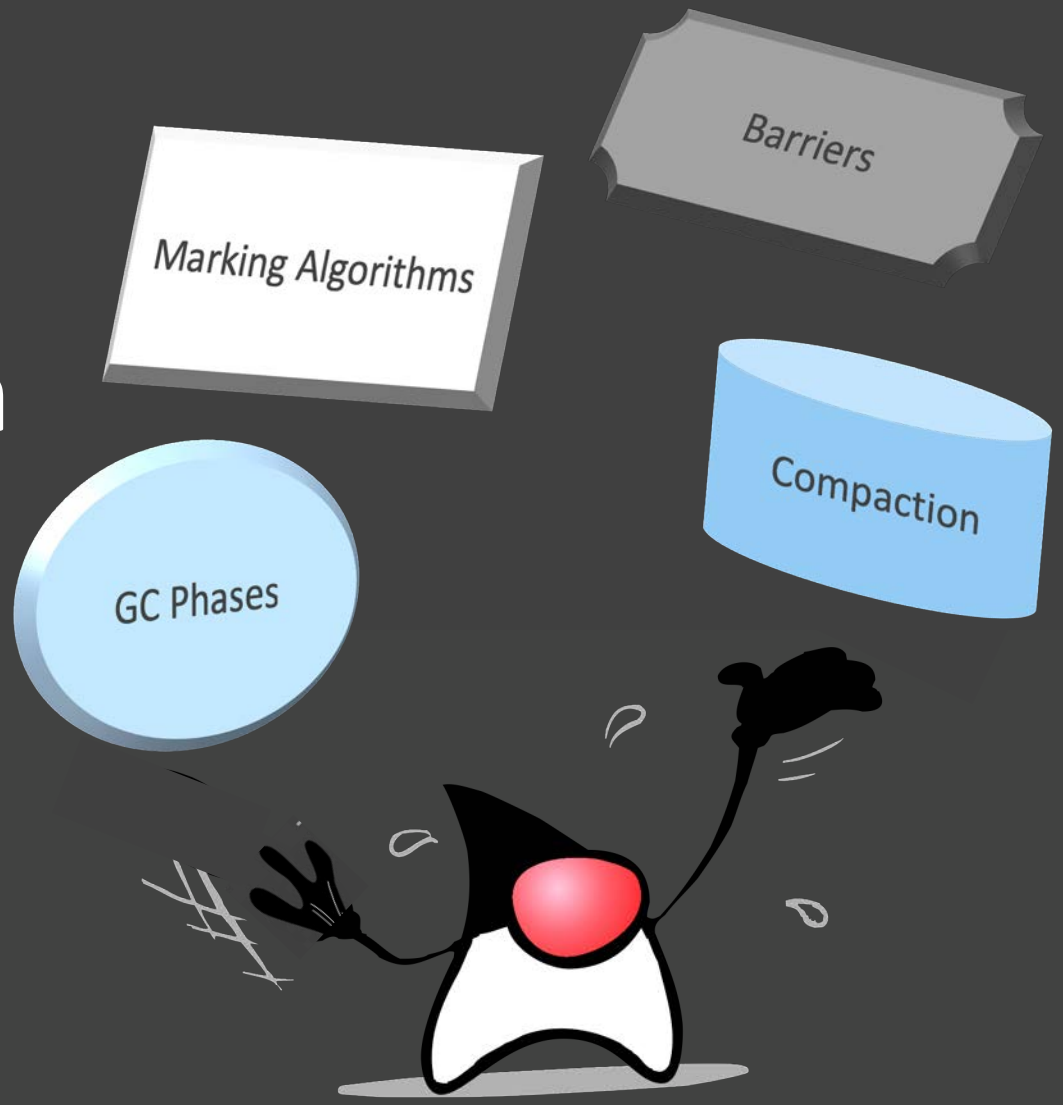
Load barrier to detect object pointers into the collection set

Can be self-healing

Off-heap forwarding tables enable to immediately release and reuse virtual and physical memory

http://cr.openjdk.java.net/~pliden/slides/ZGC-Jfokus-2018.pdf

Differences – Shenandoah



GC Phases of Marking and Compaction

Shenandoah GC	Gist
Initial Mark	Mark objects directly reachable by the roots
Concurrent Marking	Snapshot-at-the-beginning (SATB) algorithm
Final Marking	Drain SATB buffers; traverse unvisited live objects; identify collection set
Concurrent Cleanup	Free completely free regions
Concurrent Compaction	Move objects in collection set to “to” regions
Initial Update Reference	Initialize the update reference phase
Concurrent Update Reference	Scans the heap linearly; update any references to objects that have moved
Final Update Reference	Update roots to point to to-region copies
Concurrent Cleanup	Free regions in collection set

https://wiki.openjdk.java.net/display/shenandoah/Main

Concurrent Marking

Snapshot-at-the-beginning (SATB) Algorithm

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Barriers

SATB Pre-Write Barrier - Recap

Needed for all updates
Check if “marking-is-active”
SATB_enqueue the pre_val

•C. Hunt, M. Beckwith, P. Parhar, B. Rutisson. Java Performance Companion.

Barriers

Read Barrier – For Concurrent Compaction

Here's an assembly code snippet for reading a field:

```
mov 0x10(%rsi),%rsi     ; *getfield value
```

Here's what the snippet looks like with Shenandoah:

```
mov -0x8(%rsi),%rsi    ; read of forwarding pointer at address object - 0x8
mov 0x10(%rsi),%rsi    ; *getfield value
```

*Flood, Christine & Kennke, Roman & Dinn, Andrew & Haley, Andrew & Westrelin, Roland. (2016). Shenandoah: An open-source concurrent compacting garbage collector for OpenJDK. 1-9. 10.1145/2972206.2972210.

Barriers

Copying Write Barrier – For Concurrent Compaction

Needed for all updates to ensure to-space invariant
Check if “evacuation_in_progress”
Check if “in_collection_set” and “not_yet_copied”
CAS (fwd-ptr(obj), obj, copy)

*Flood, Christine & Kennke, Roman & Dinn, Andrew & Haley, Andrew & Westrelin, Roland. (2016). Shenandoah: An open-source concurrent compacting garbage collector for OpenJDK. 1-9. 10.1145/2972206.2972210.

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Superseded

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Barriers

Loaded Reference Barrier - Recap

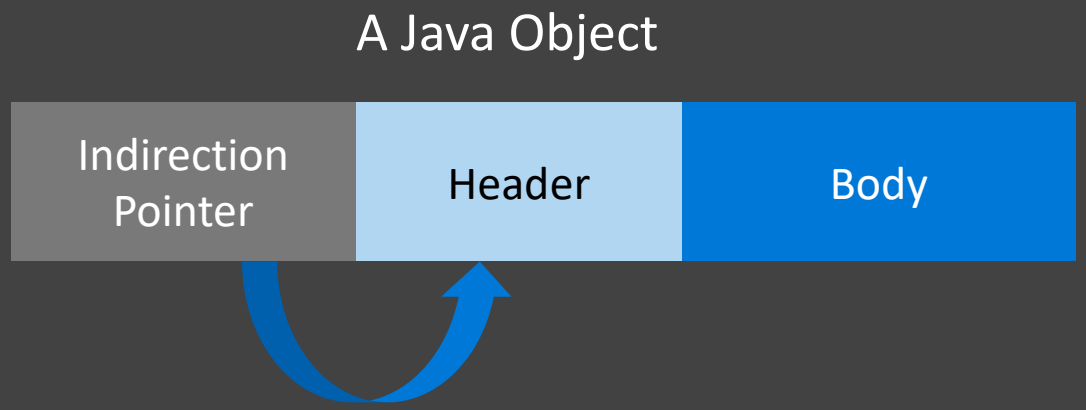
Ensure strong ‘to-space invariant’
Utilize barriers at reference load
Check if fast-path-possible; else do-slow-path

https://developers.redhat.com/blog/2019/06/27/shenandoah-gc-in-jdk-13-part-1-load-reference-barriers/

Tene, G.; Iyengar, B. & Wolf, M. (2011), C4: The Continuously Concurrent Compacting Collector, *in* 'Proceedings of the international symposium on Memory management' , ACM, New York, NY, USA , pp. 79--88 .

Concurrent Compaction

Brooks Style Indirection Pointer

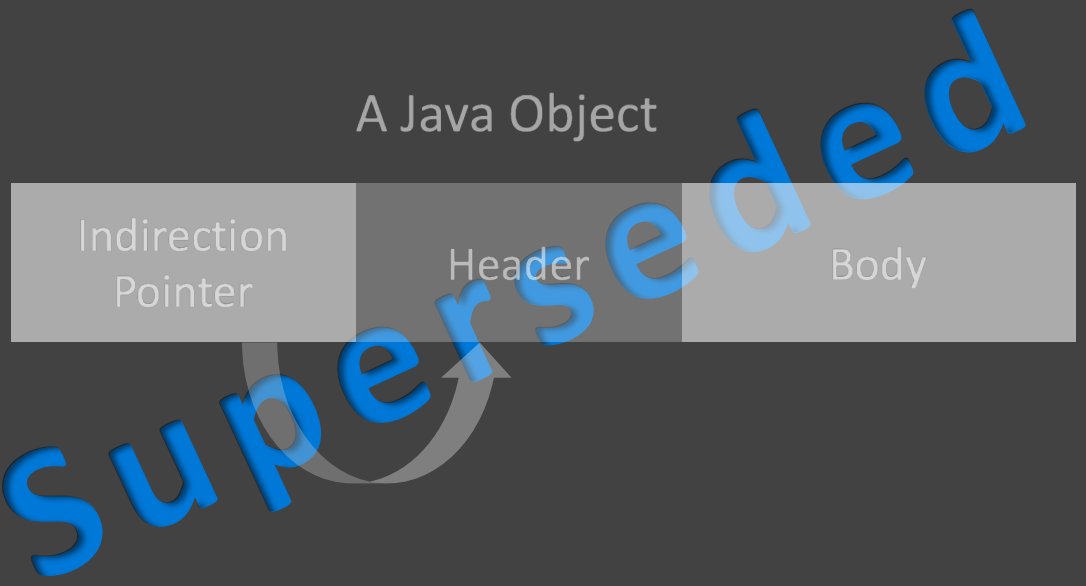


Forwarding pointer is placed before the object

Additional work of dereferencing per object

Concurrent Compaction

Brooks Style Indirection Pointer



Forwarding pointer is placed before the object

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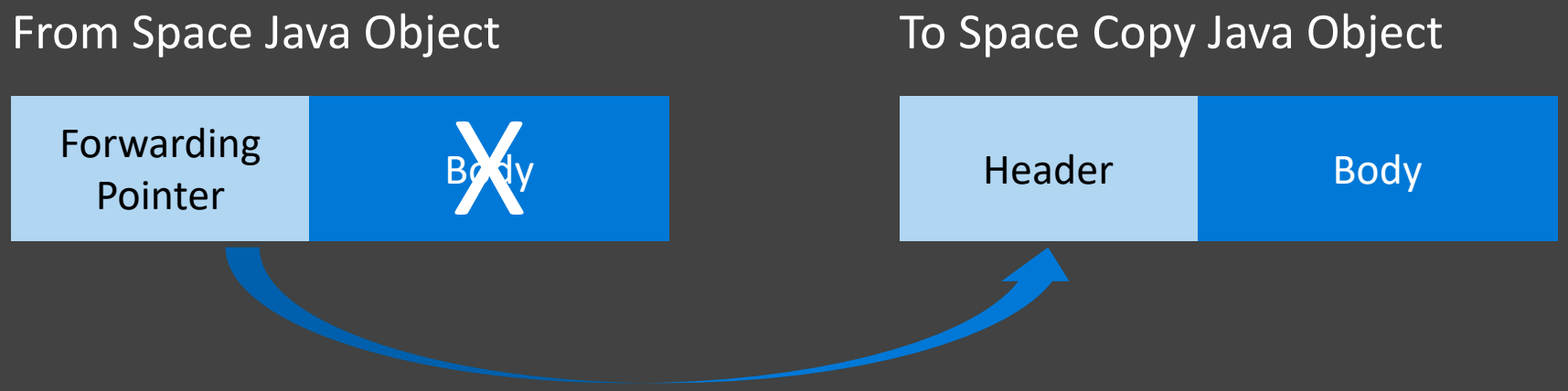
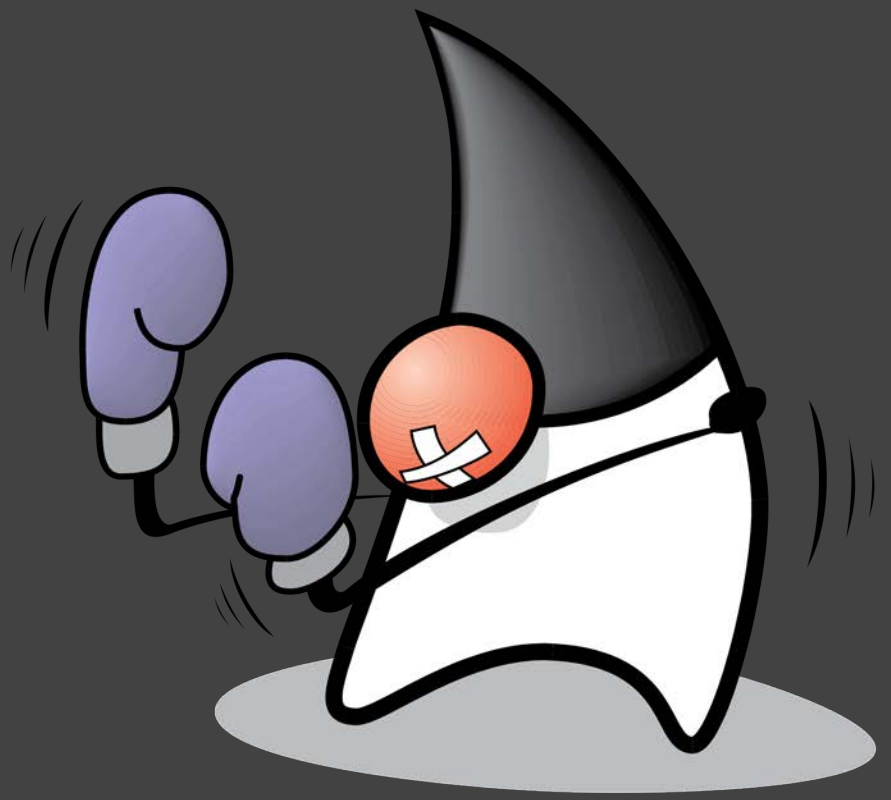
Concurrent Compaction

Forwarding Pointer in Header



https://developers.redhat.com/blog/2019/06/28/shenandoah-gc-in-jdk-13-part-2-eliminating-the-forward-pointer-word/

Performance!



Test Setup

Azure VM

Azure VM + Linux:

Intel(R) Xeon(R) CPU E5-2673 v3 @ 2.40GHz

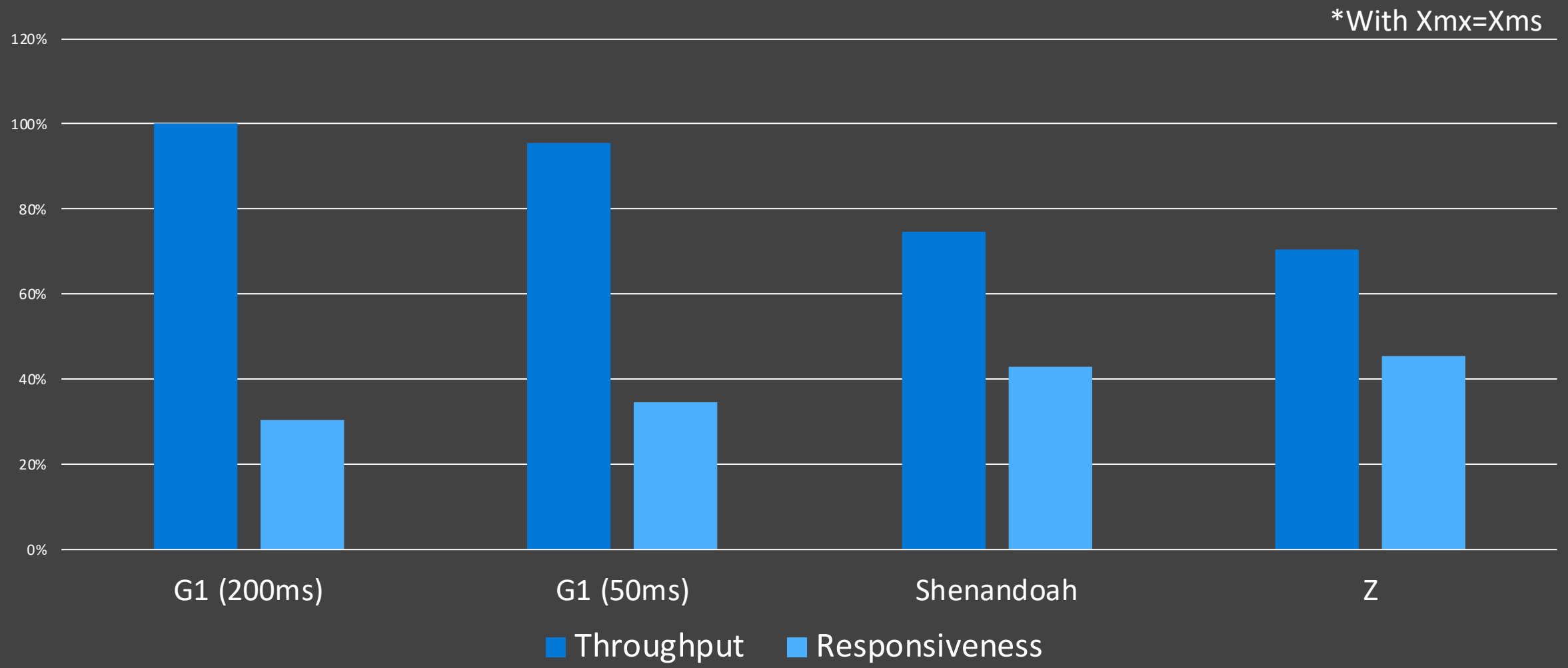
16GB; 4 cores

https://adoptopenjdk.net/releases.html#x64_linux

AdoptOpenJDK

Out-of-box* GC Performance

Throughput and Responsiveness



Further Reading

https://www.youtube.com/watch?v=VCeHkcwfF9Q

https://www.usenix.org/legacy/events/vee05/full_papers/p46-click.pdf

http://mail.openjdk.java.net/pipermail/zgc-dev/2017-December/000047.html

http://hg.openjdk.java.net/zgc/zgc/file/ffab403eaf14/src/hotspot/share/gc/z/zBarrier.cpp

https://wiki.openjdk.java.net/display/zgc/Main