The Z Garbage Collector

Low Latency GC for OpenJDK

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Jfokus VM Tech Summit 2018

Safe Harbor Statement

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Agenda

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1. What is ZGC?
2. Some Numbers
3. Under The Hood
4. Going Forward
5. How To Get Started

A Scalable Low Latency Garbage Collector

Goals

TB Multi-terabyte heaps

10ms Max GC pause time

Lay the foundation for future GC features

15% Max application throughput reduction

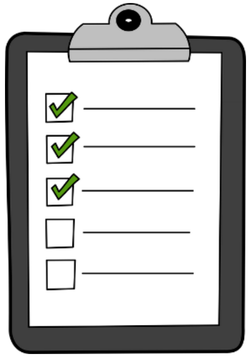
GC pause times **do not** increase with heap or live-set size

At a Glance

- New garbage collector
- Load barriers
- Colored pointers
- Single generation
- Partial compaction
- Region-based
- Immediate memory reuse
- NUMA-aware

- Concurrent
  - ✓ Marking
  - ✓ Relocation/Compaction
  - ✓ Relocation Set Selection
  - ✓ Reference Processing
  - ✓ JNI WeakRefs Cleaning
  - \- StringTable/SymbolTable Cleaning
  - \- Class Unloading

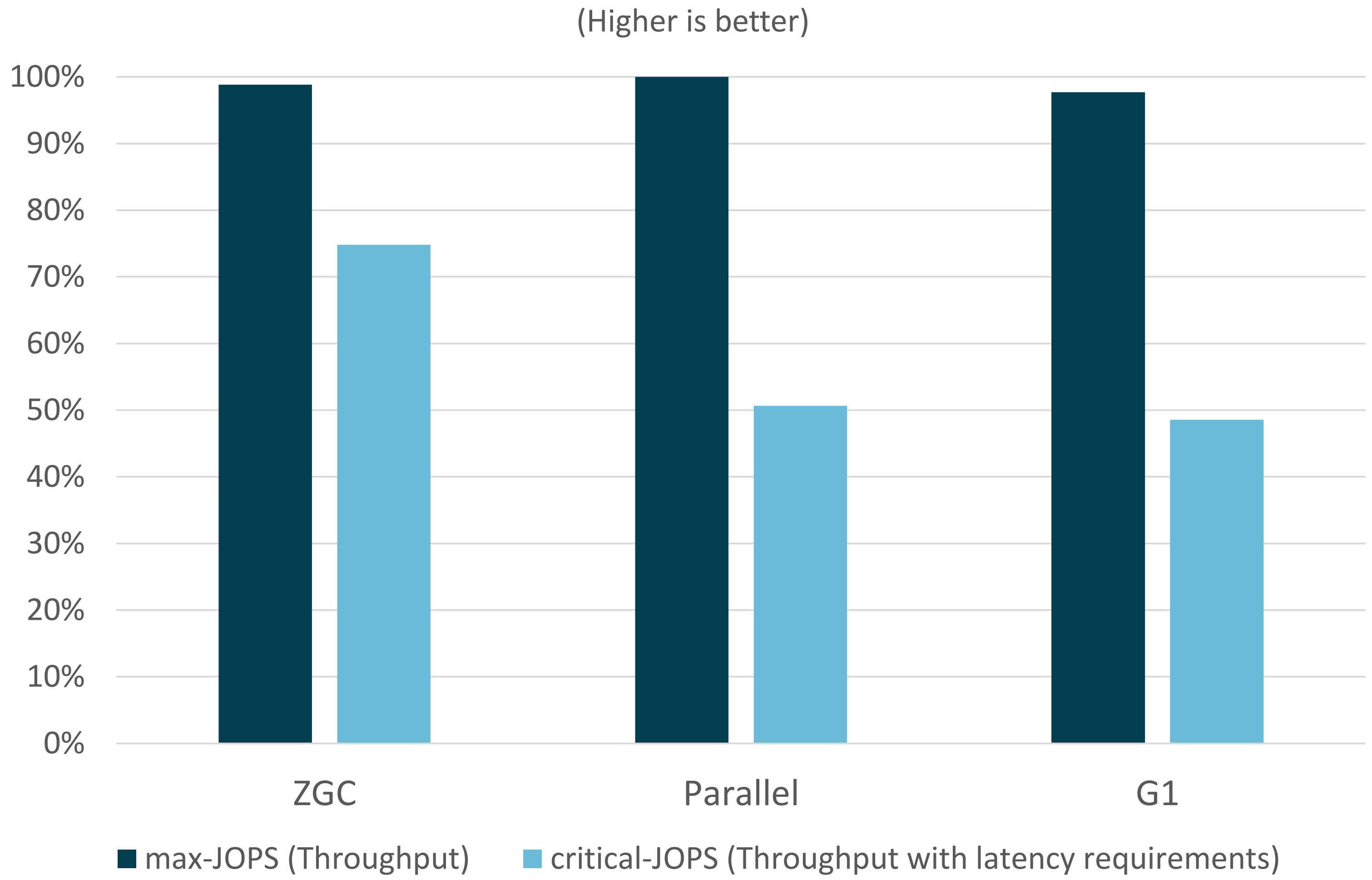
Current Status



- Design and implementation approaching mature and stable
- Main focus on **Linux/x86_64**
  – Other platforms can be added if there’s enough demand
- Performance looks very good
  – Both in terms of latency and throughput

Agenda

SPECjbb®2015 – Score



Mode: Composite

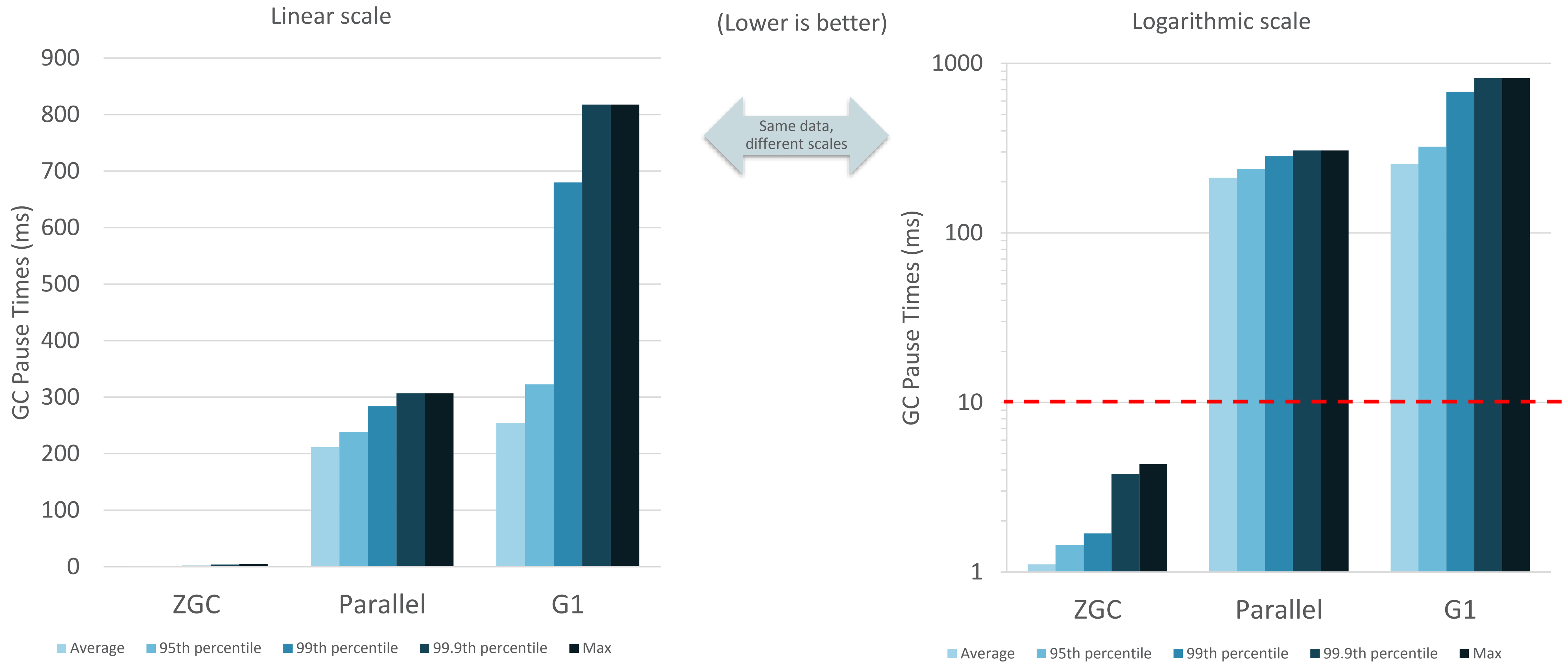
Heap Size: 128G

OS: Oracle Linux 7.4

HW: Intel Xeon E5-2690 2.9GHz
2 sockets, 16 cores (32 hw-threads)

SPECjbb®2015 is a registered trademark of the Standard Performance Evaluation Corporation (spec.org). The actual results are not represented as compliant because the SUT may not meet SPEC's requirements for general availability.

SPECjbb®2015 – Pause Times



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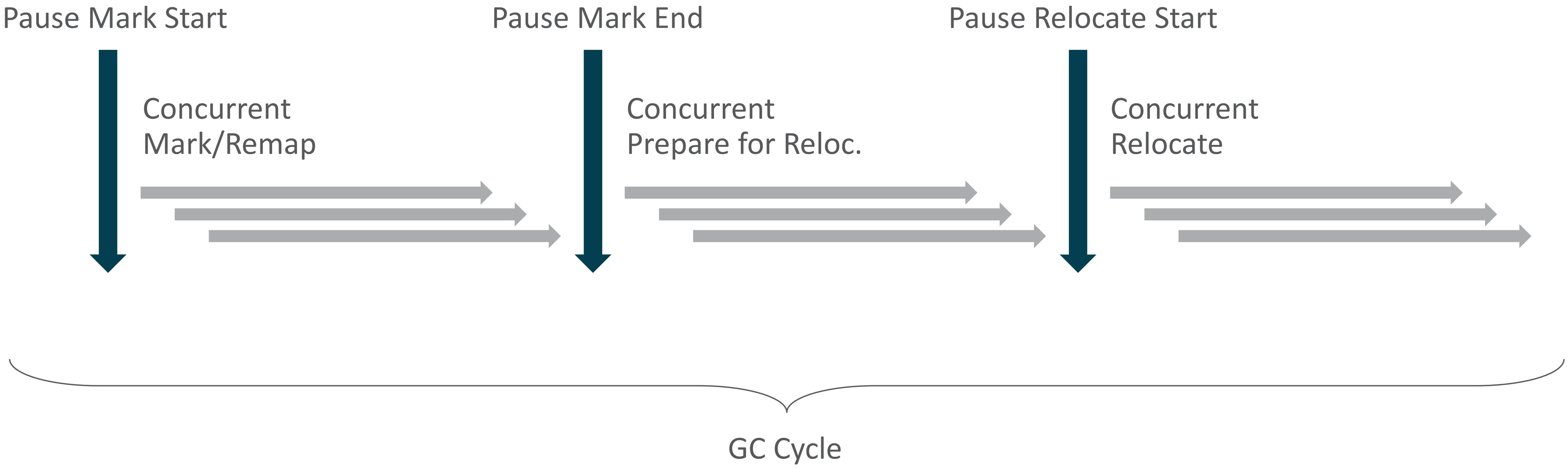
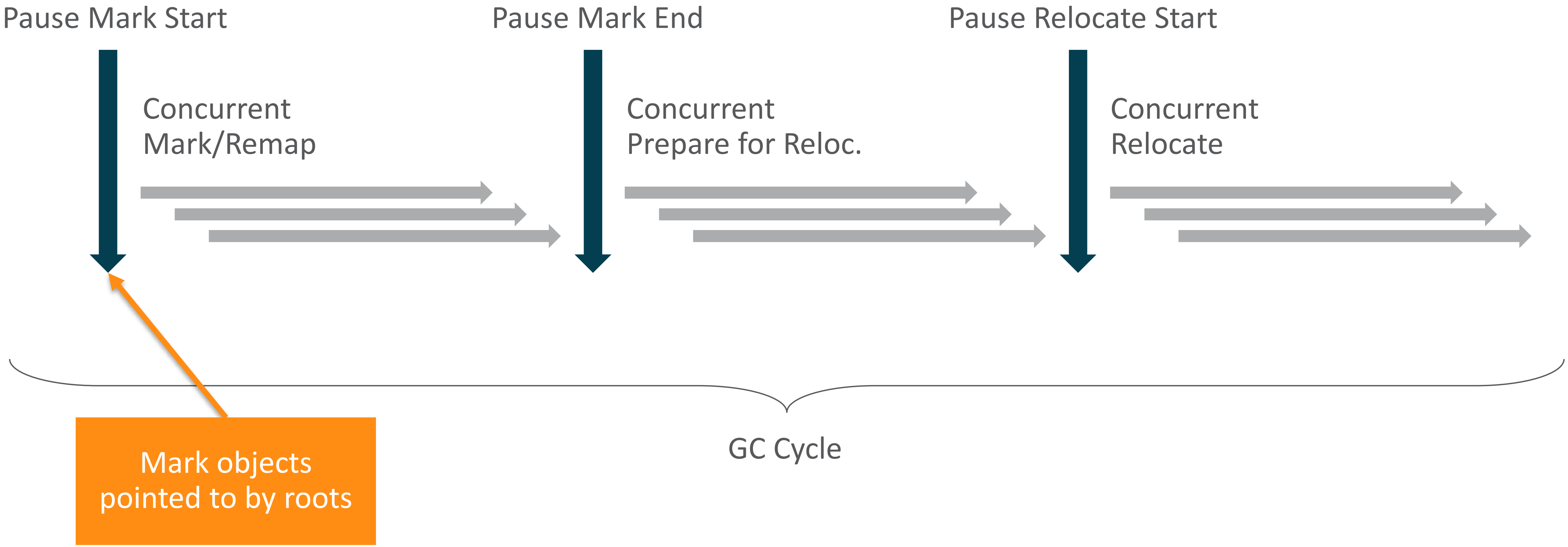
ZGC Phases

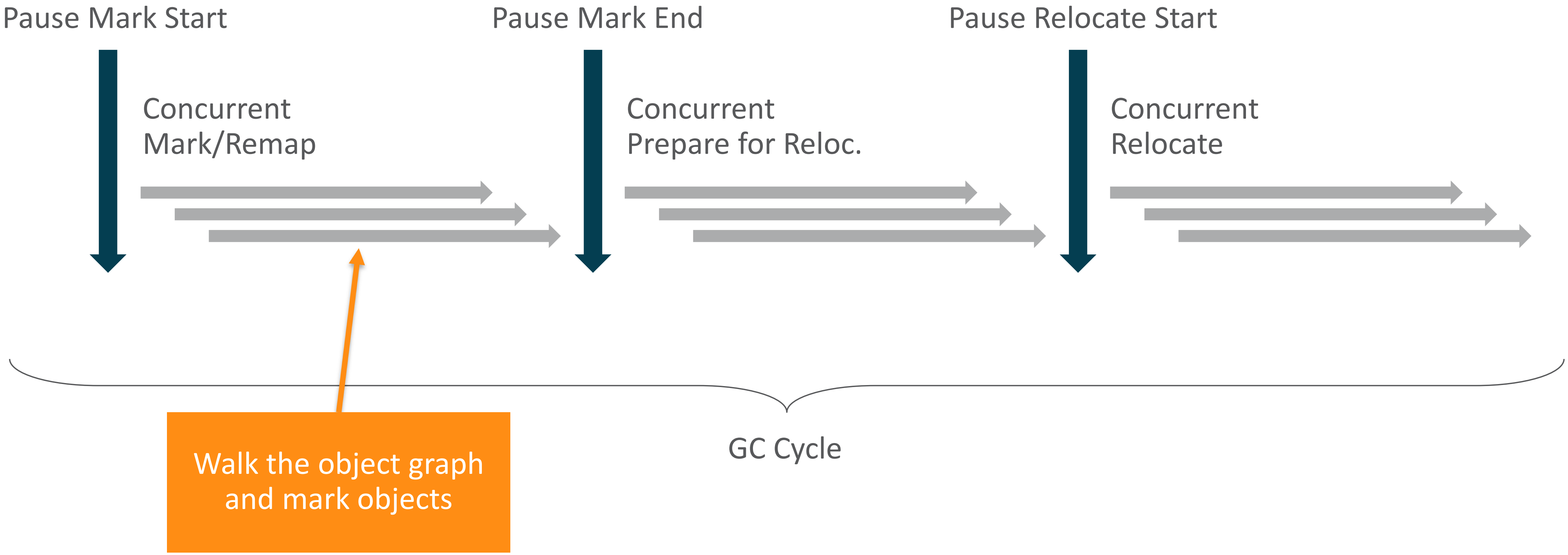


Pause Mark Start
Pause Mark End
Pause Relocate Start
Concurrent
Mark/Remap
Concurrent
Prepare for Reloc.
Concurrent
Relocate
GC Cycle

ZGC Phases

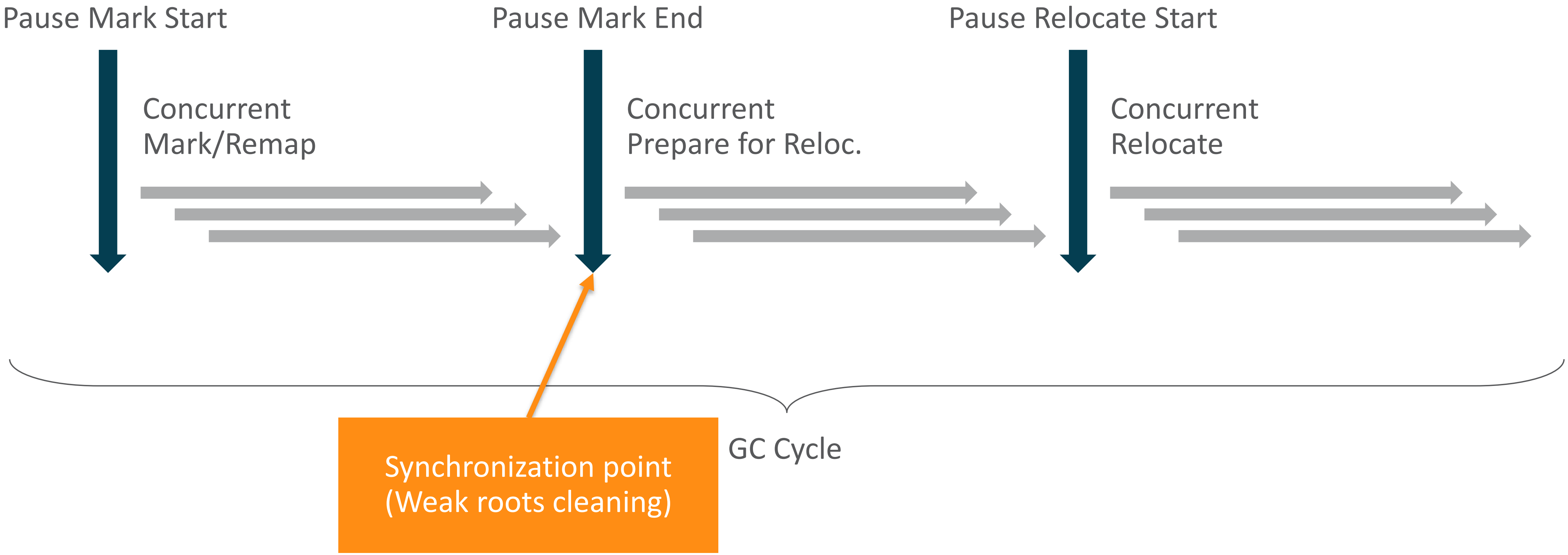

Pause Mark Start
Pause Mark End
Pause Relocate Start
Concurrent Mark/Remap
Concurrent Prepare for Reloc.
Concurrent Relocate
GC Cycle
Mark objects pointed to by roots

ZGC Phases

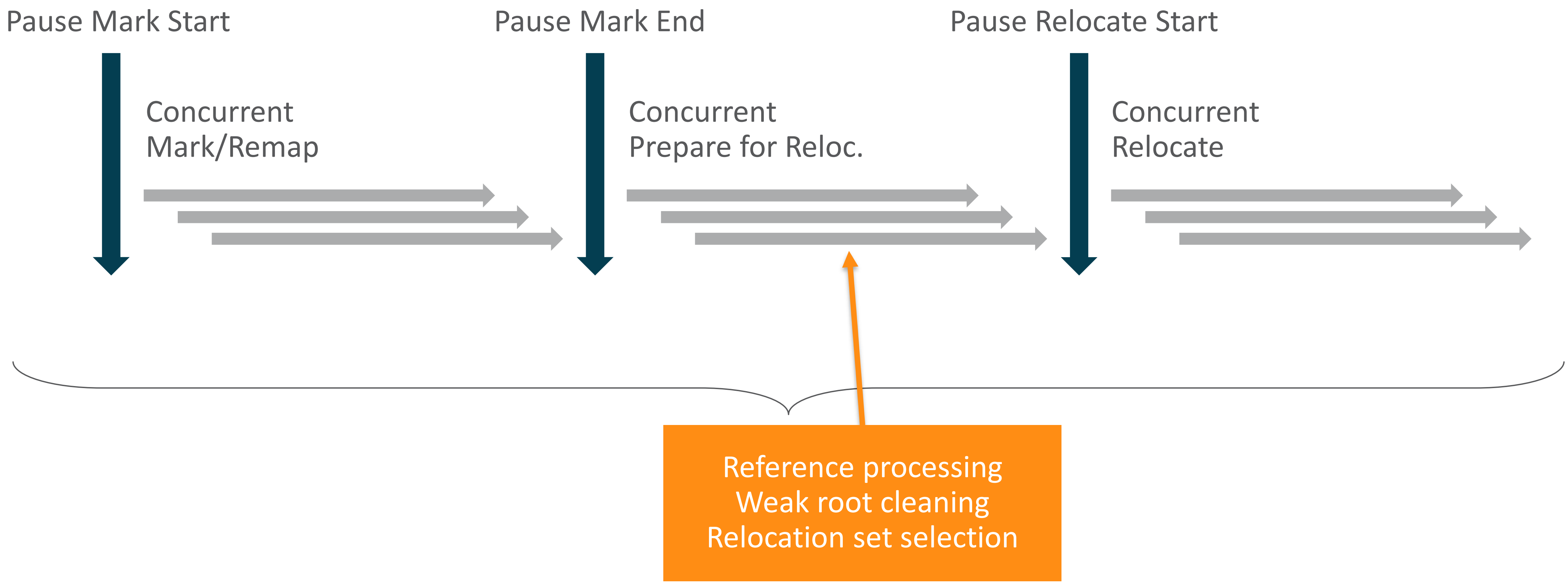


Pause Mark Start
Pause Mark End
Pause Relocate Start
Concurrent
Mark/Remap
Concurrent
Prepare for Reloc.
Concurrent
Relocate
GC Cycle
Walk the object graph
and mark objects

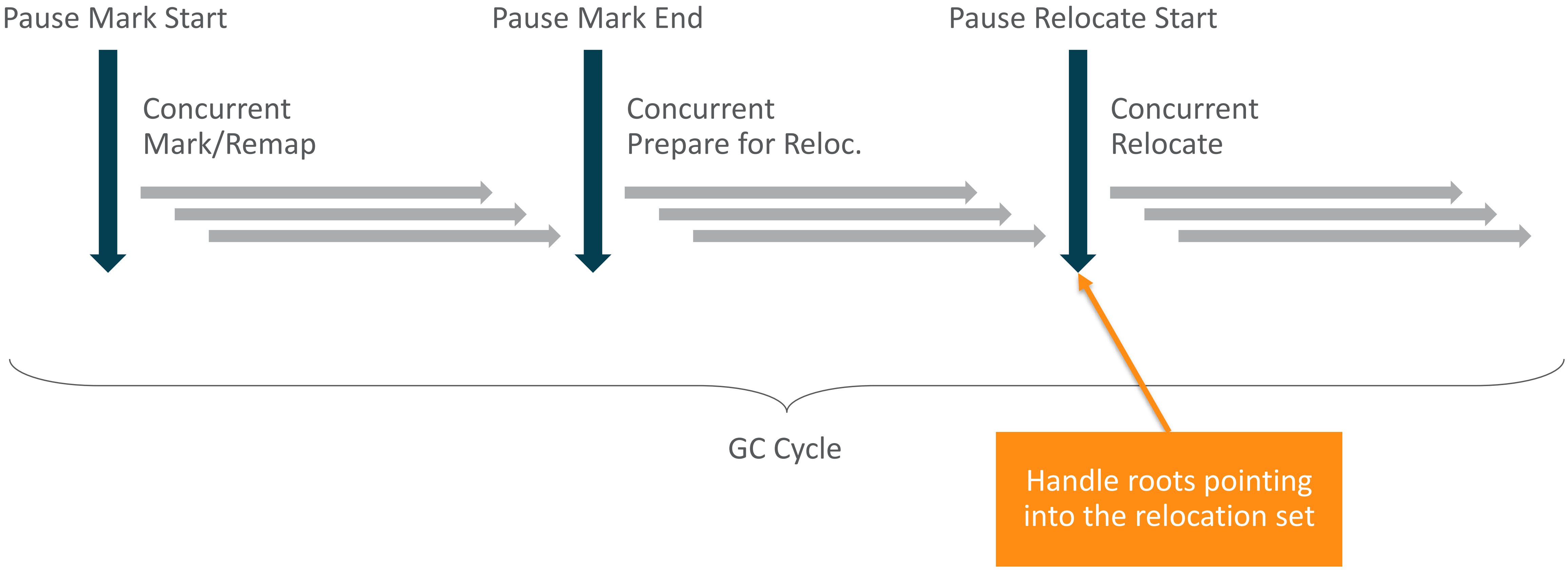
ZGC Phases


Pause Mark Start
Pause Mark End
Pause Relocate Start
Concurrent
Mark/Remap
Concurrent
Prepare for Reloc.
Concurrent
Relocate
Synchronization point
(Weak roots cleaning)
GC Cycle

ZGC Phases

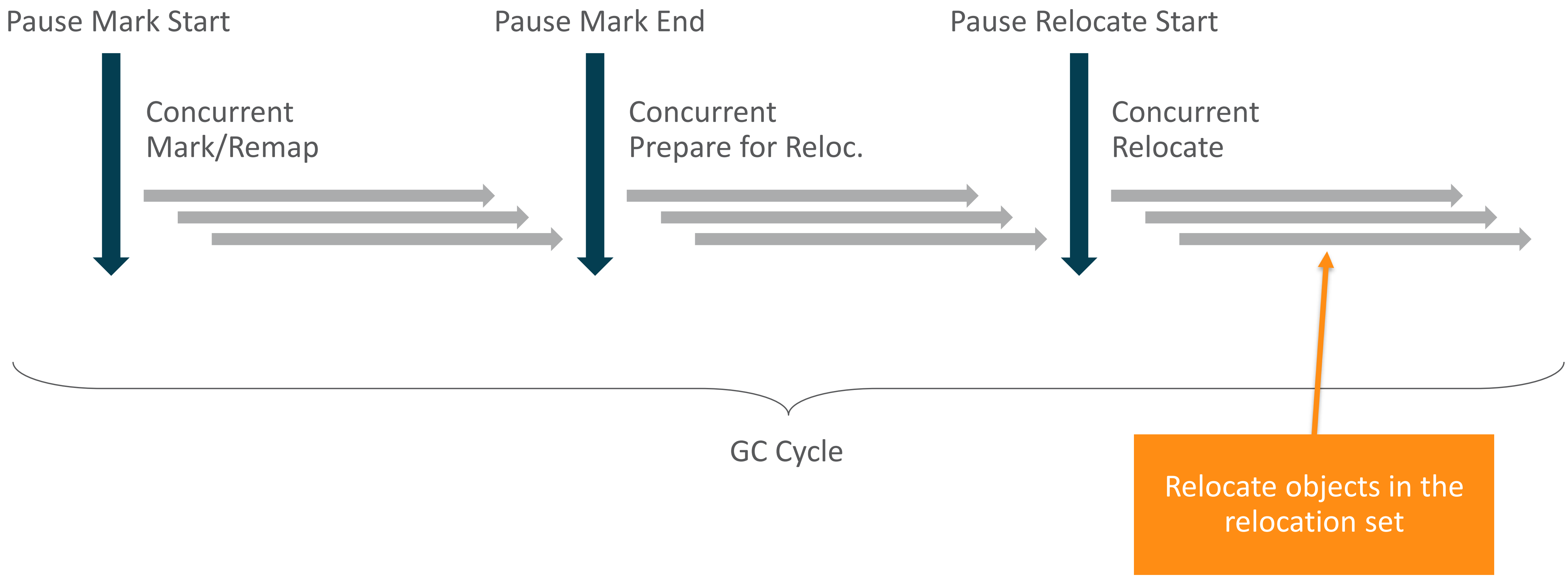

Pause Mark Start
Pause Mark End
Pause Relocate Start
Concurrent Mark/Remap
Concurrent Prepare for Reloc.
Concurrent Relocate
Reference processing
Weak root cleaning
Relocation set selection

ZGC Phases

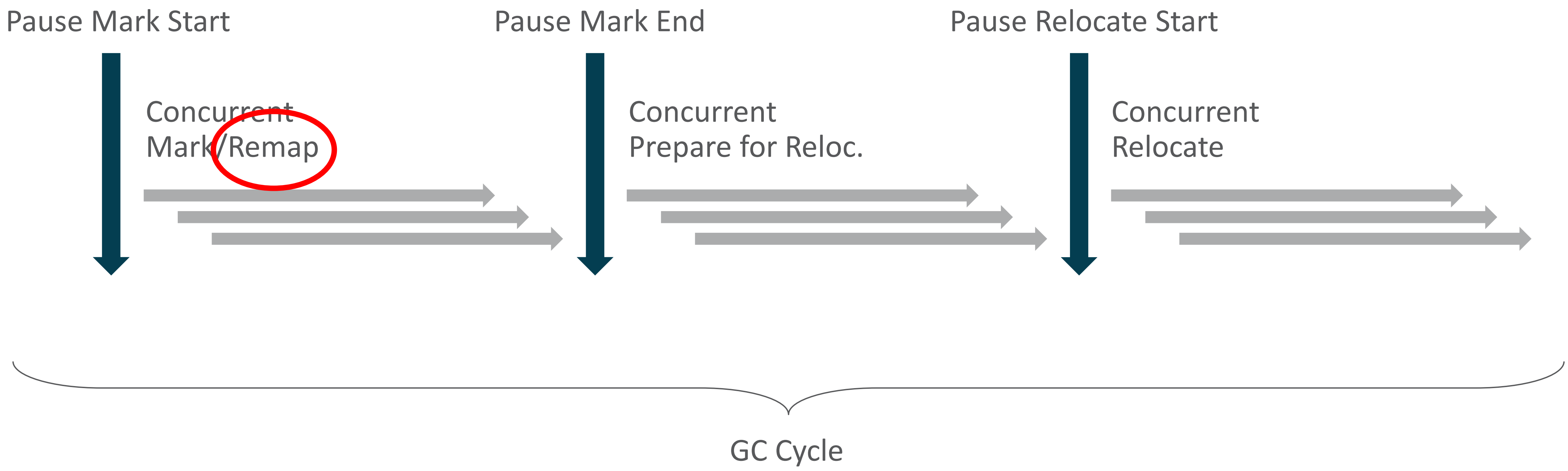


Pause Mark Start
Pause Mark End
Pause Relocate Start
Concurrent Mark/Remap
Concurrent Prepare for Reloc.
Concurrent Relocate
GC Cycle
Handle roots pointing into the relocation set

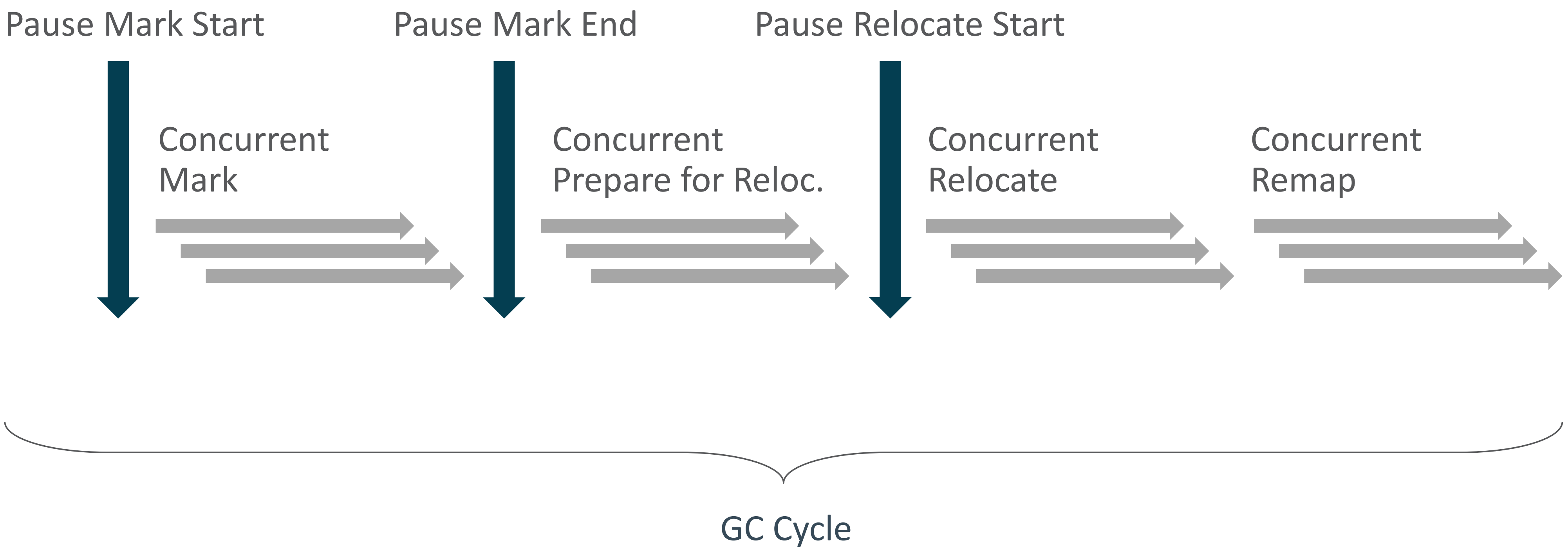
ZGC Phases


Pause Mark Start
Pause Mark End
Pause Relocate Start
Concurrent
Mark/Remap
Concurrent
Prepare for Reloc.
Concurrent
Relocate
GC Cycle
Relocate objects in the relocation set

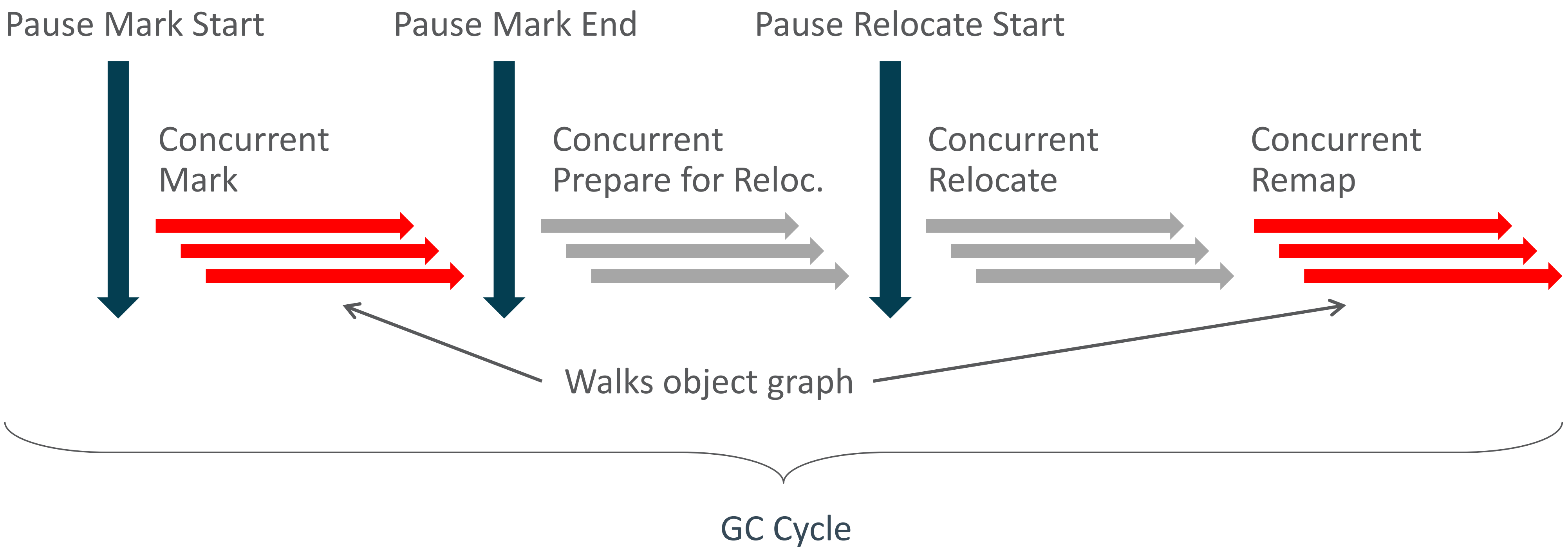
ZGC Phases


Pause Mark Start
Pause Mark End
Pause Relocate Start
Concurrent
Mark/Remap
Concurrent
Prepare for Reloc.
Concurrent
Relocate
GC Cycle

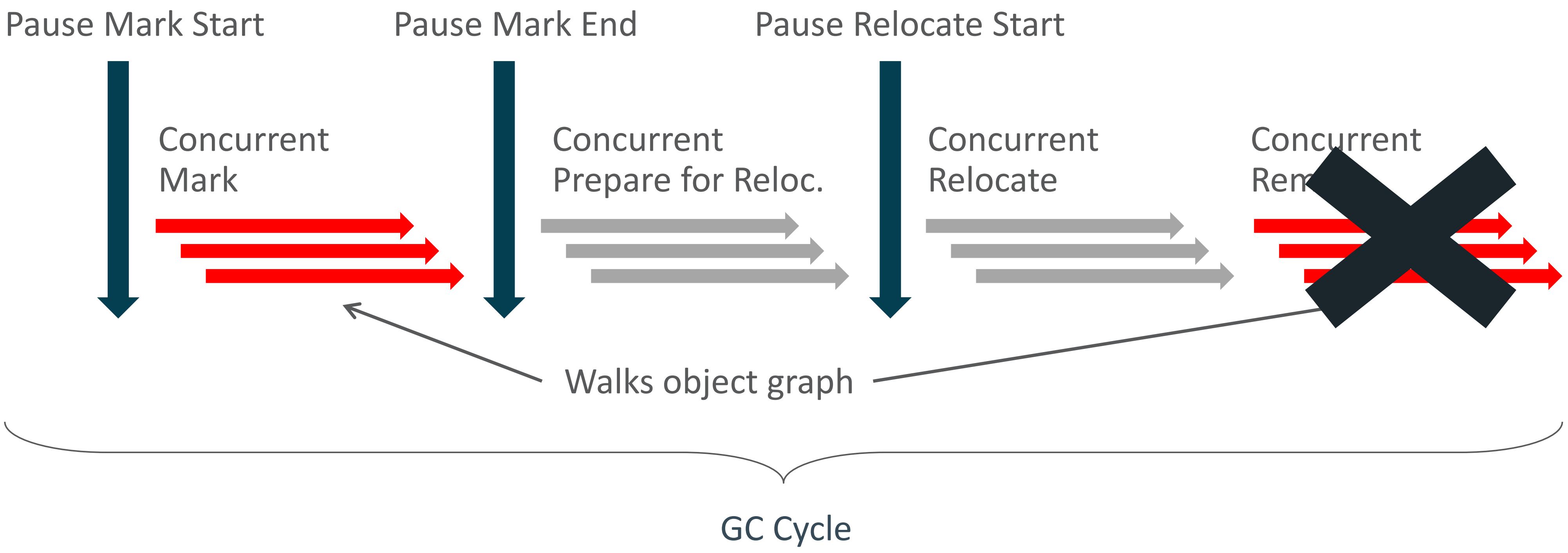
ZGC Phases


Pause Mark Start
Pause Mark End
Pause Relocate Start
Concurrent Mark
Concurrent Prepare for Reloc.
Concurrent Relocate
Concurrent Remap
GC Cycle

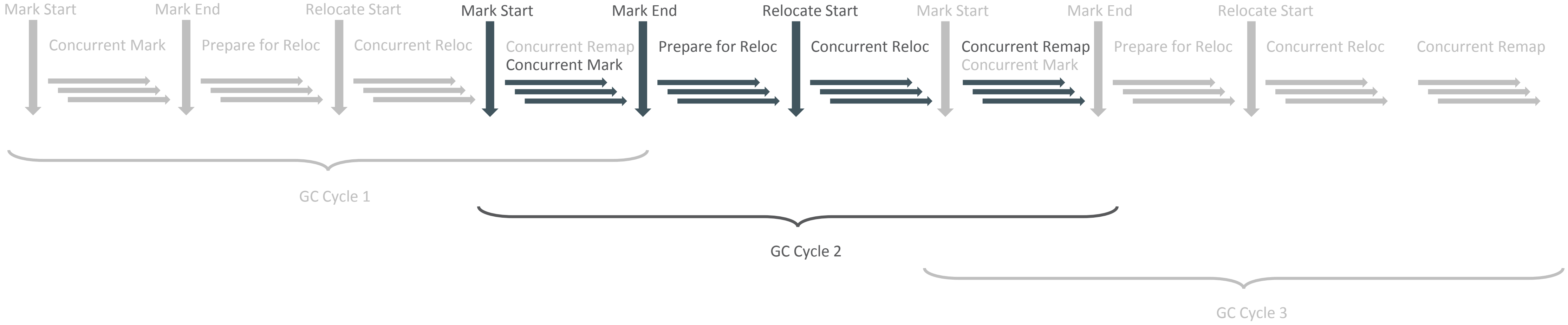
ZGC Phases


Pause Mark Start
Pause Mark End
Pause Relocate Start
Concurrent
Mark
Concurrent
Prepare for Reloc.
Concurrent
Relocate
Concurrent
Remap
Walks object graph
GC Cycle

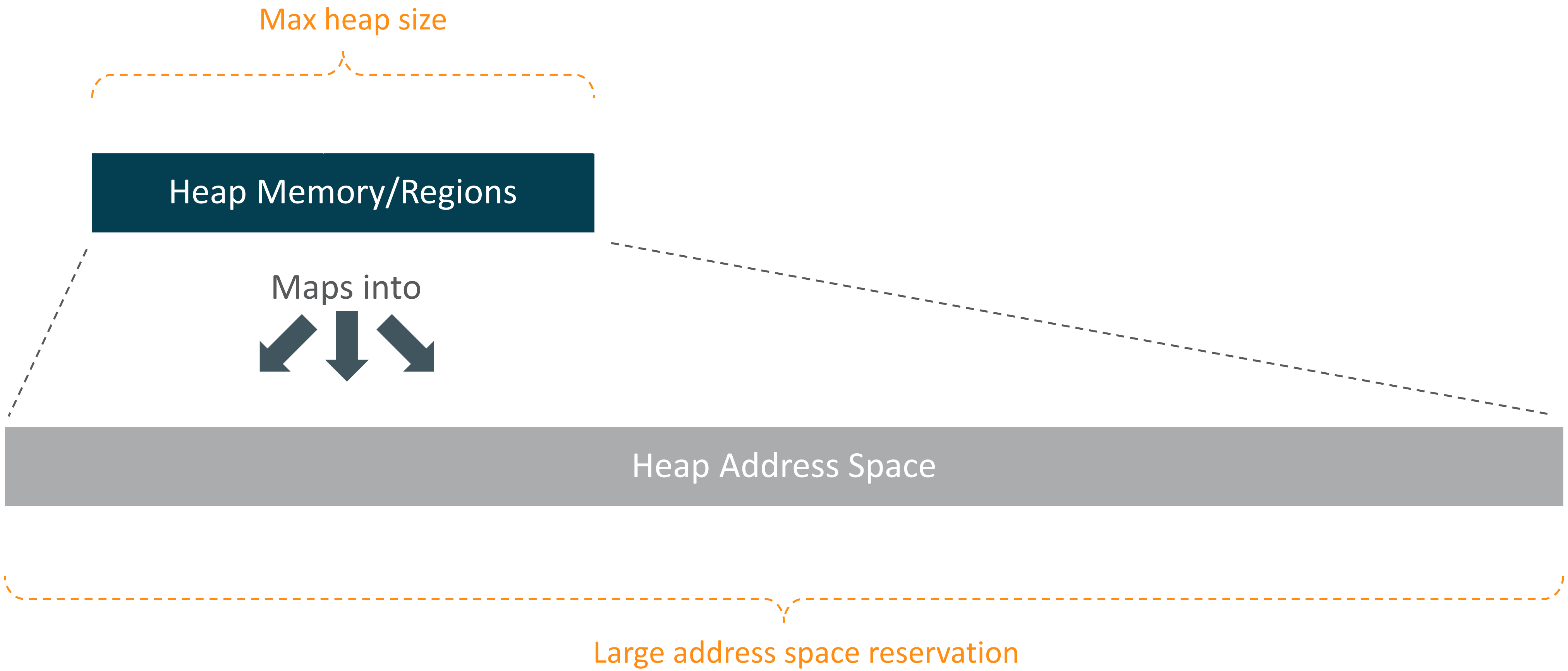
ZGC Phases


Pause Mark Start
Pause Mark End
Pause Relocate Start
Concurrent
Mark
Concurrent
Prepare for Reloc.
Concurrent
Relocate
Concurrent
Rem
Walks object graph
GC Cycle

ZGC Phases


Mark Start
Mark End
Relocate Start
Mark Start
Mark End
Relocate Start
Mark Start
Mark End
Relocate Start
Concurrent Mark
Prepare for Reloc
Concurrent Reloc
Concurrent Remap
Concurrent Mark
Prepare for Reloc
Concurrent Reloc
Concurrent Remap
Concurrent Mark
Prepare for Reloc
Concurrent Reloc
Concurrent Remap
GC Cycle 1
GC Cycle 2
GC Cycle 3

Heap Address Space



Heap Regions

Also known as ZPages

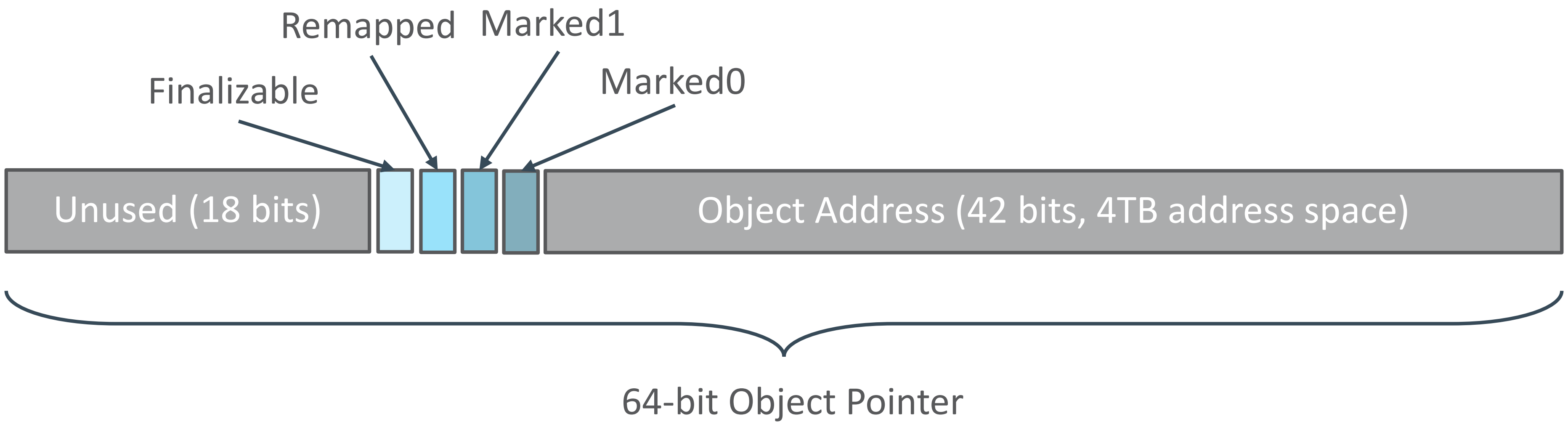
- Dynamically created/destroyed
- Dynamically sized
  - Multiple of **2MB** on **x86_64**
- Size groups
  - **Small** (2MB)
  - **Medium** (32MB)
  - **Large** (N x 2MB)

Colored Pointers

- Core design concept in ZGC
- **Metadata** stored in unused bits in 64-bit pointers
  - No support for 32-bit platforms
  - No support for CompressedOops
- **Virtual Address-masking** either in hardware, OS or software
  - Heap multi-mapping on Linux/x86_64
  - Supported in hardware on Solaris/SPARC

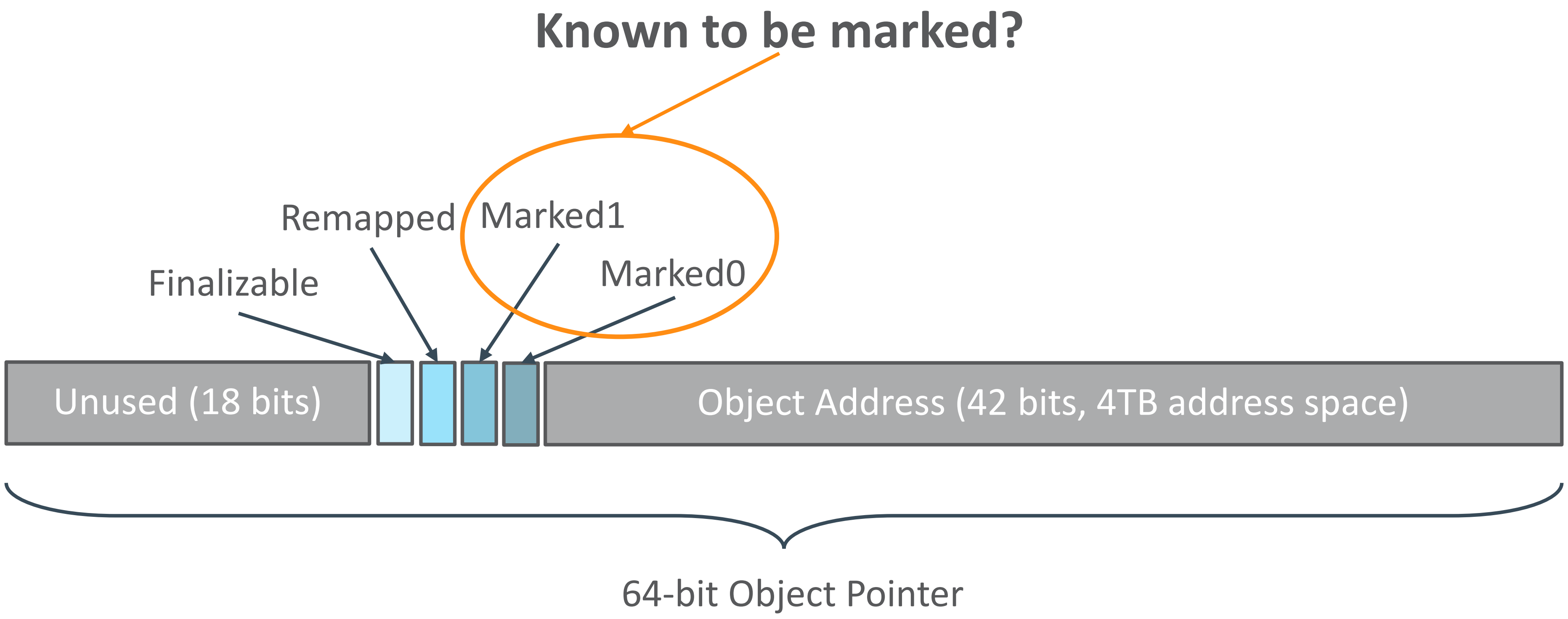
Colored Pointers

Layout on x86_64



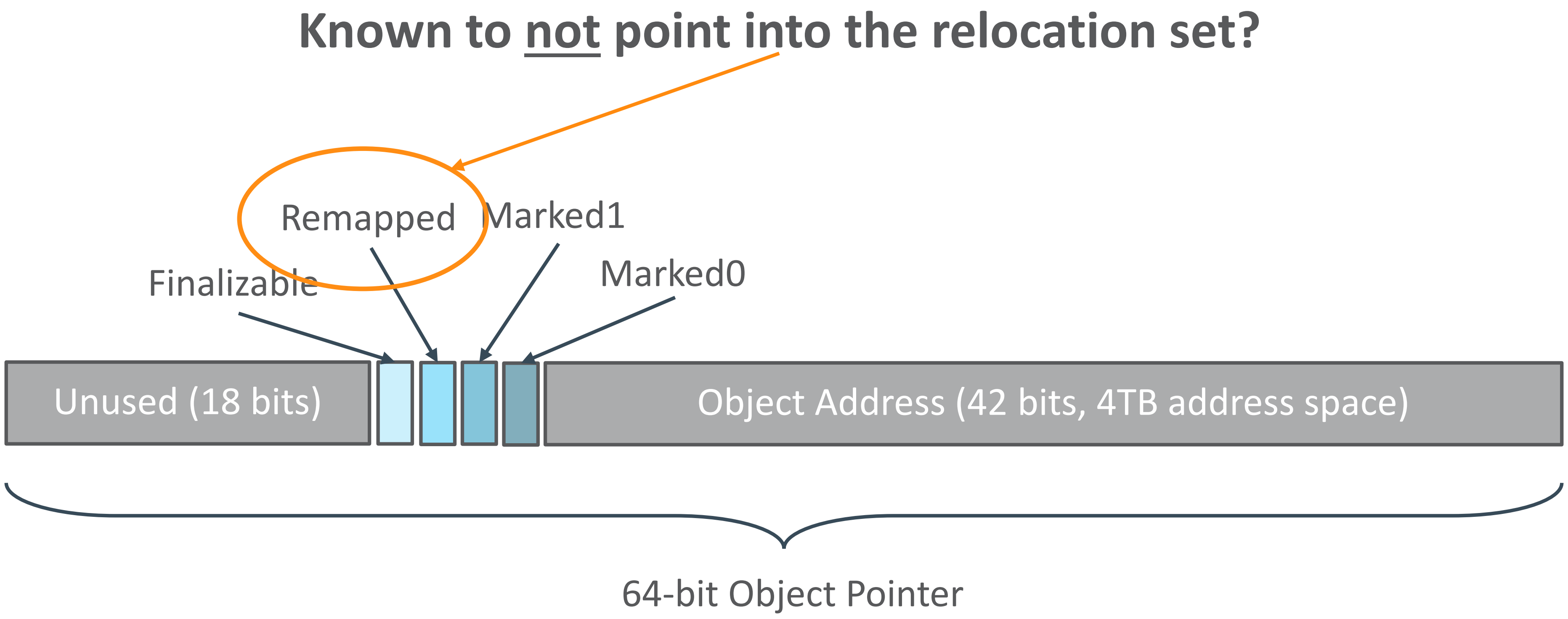
Colored Pointers

Layout on x86_64



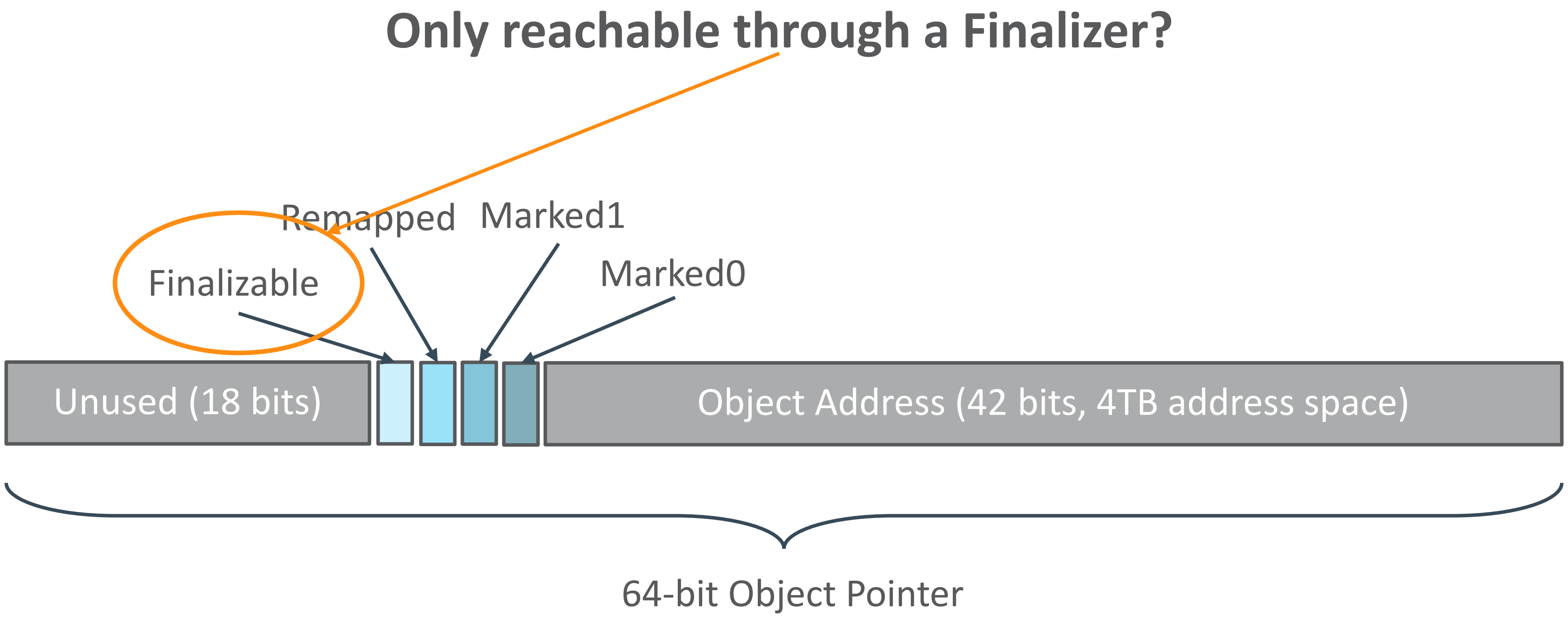
Colored Pointers

Layout on x86_64



Colored Pointers

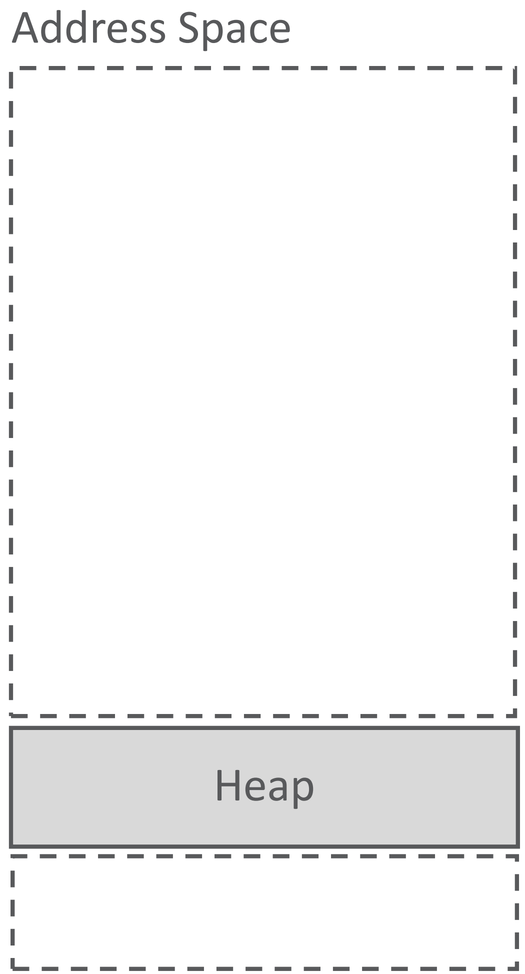
Layout on x86_64



Heap Multi-Mapping on **Linux/x86_64**

Heap Mapping on **Solaris/SPARC**

- Single heap mapping
- Virtual address masking in hardware
- **Load** and **store** instructions mask out metadata bits



(ARM AArch64 also supports this)

Load Barrier

- Applied when **loading an object reference** from the heap
  - **Not** when later using that reference to access the object
  - Conceptually similar to the decoding of compressed oops

- Looks at the color of the pointer
  - Take action if the pointer has a “**bad**” color (mark/relocate/remap)
  - Change to the “**good**” color (repair/heal)

- Optimized for the common case
  - Most object references will have the “**good**” color

Load Barrier

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

Load Barrier

```
Object o = obj.fieldA;          // Loading an object reference from heap
<load barrier needed here>
```

Load Barrier

```
Object o = obj.fieldA;          // Loading an object reference from heap
<load barrier needed here>
Object p = o;                   // No barrier, not a load from heap
o.doSomething();                // No barrier, not a load from heap
int i = obj.fieldB;             // No barrier, not an object reference
```

Load Barrier

```
Object o = obj.fieldA;          // Loading an object reference from heap
<load barrier needed here>
```

Load Barrier

```
Object o = obj.fieldA;          // Loading an object reference from heap
load_barrier(register_for(o), address_of(obj.fieldA));
```

Load Barrier

```
Object o = obj.fieldA;          // Loading an object reference from heap
if (!(o & good_bit_mask)) {
  if (o != null) {
    slow_path(register_for(o), address_of(obj.fieldA));
  }
}
```

Load Barrier

```
Object o = obj.fieldA;          // Loading an object reference from heap
if (o & bad_bit_mask) {
  slow_path(register_for(o), address_of(obj.fieldA));
}
```

Load Barrier

```
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
```

Load Barrier

```
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
```

~4% execution overhead on **SPECjbb®2015**

Load Barrier (**r12 version**)

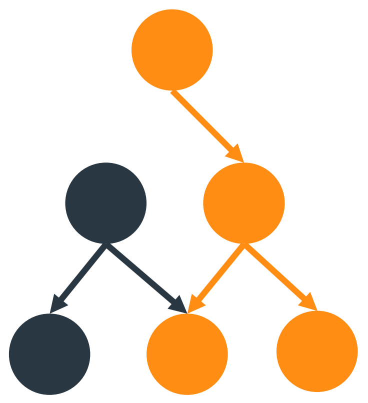
```
mov     0x20(%rax), %rbx        // Object o = obj.fieldA;
test    %rbx, %r12              // Bad color?
jnz     slow_path               // Yes -> Enter slow path and
                                // mark/relocate/remap, adjust
                                // 0x20(%rax) and %rbx
```

Always keep **bad_bit_mask** in **r12**

- Avoids a memory load, but reserves a register
- We don't support compressed oops, so we can repurpose r12, the heap base register

Mark

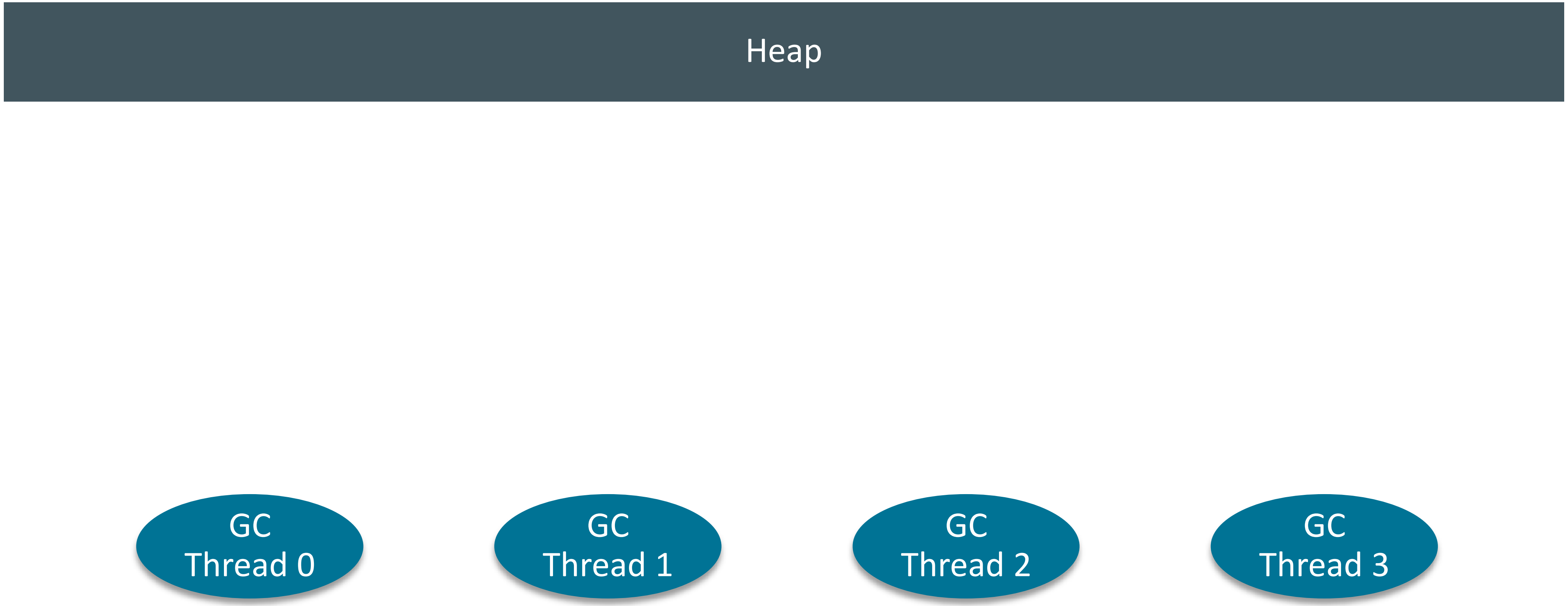
- Concurrent & Parallel
- Load barrier
  – Detects loads of non-marked object pointers
- Finalizable mark
  – Enabler for Concurrent Reference Processing
- Thread local handshakes
  – Used to synchronize end of concurrent mark
- Striped



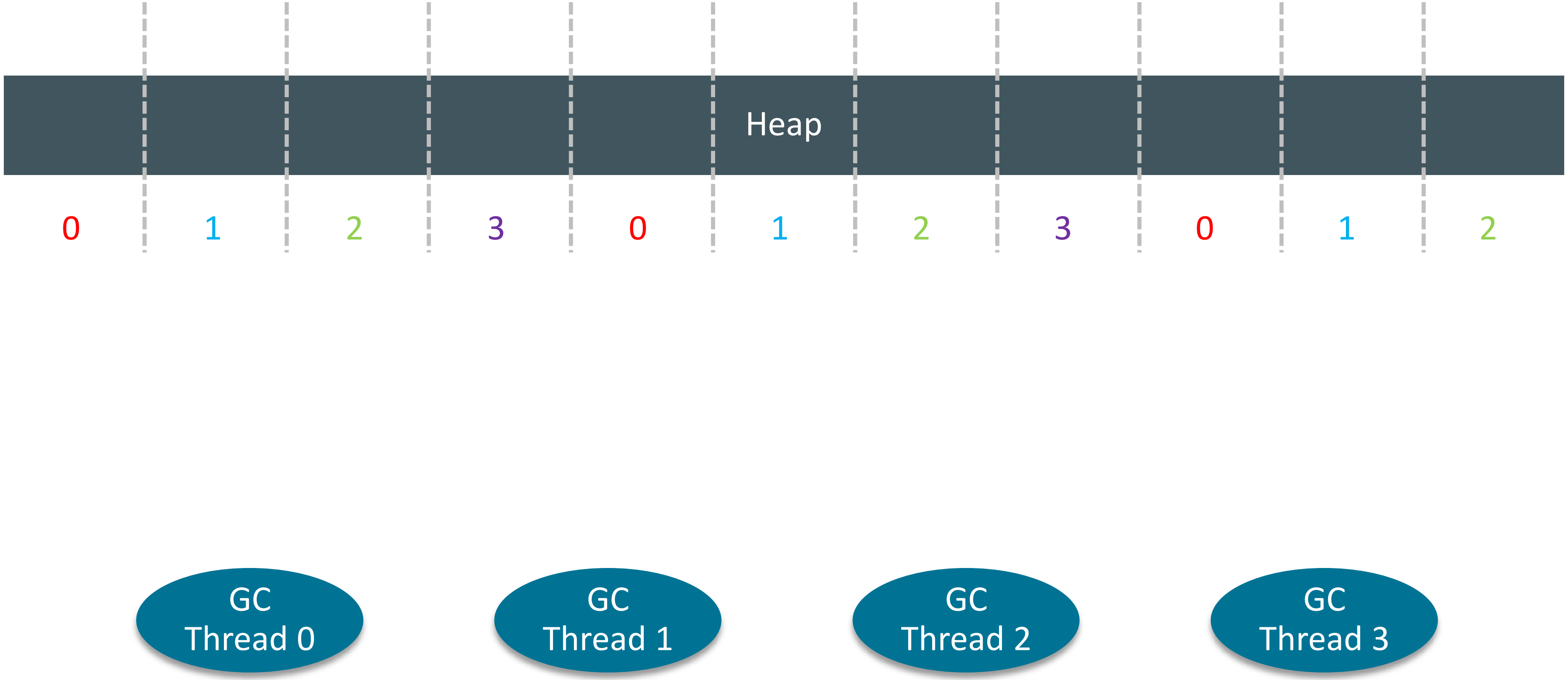
Striped Mark

- Scalability
  - Heap divided into logical stripes
  - Isolate each GC thread to work on its own stripe
  - Minimized shared state
- **Edge** pushing vs. **Node** pushing
  - Potentially more work
  - … but lends itself better to parallel processing

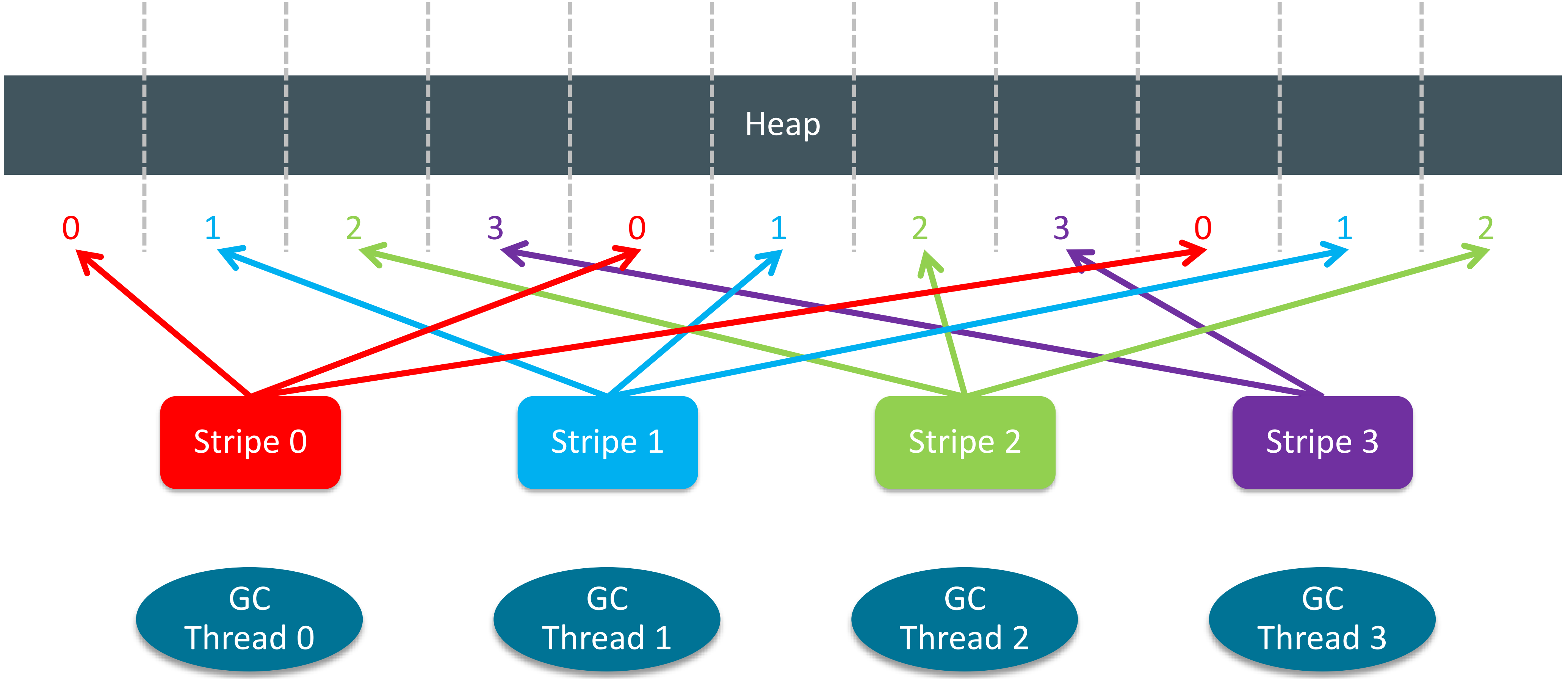
Striped Mark



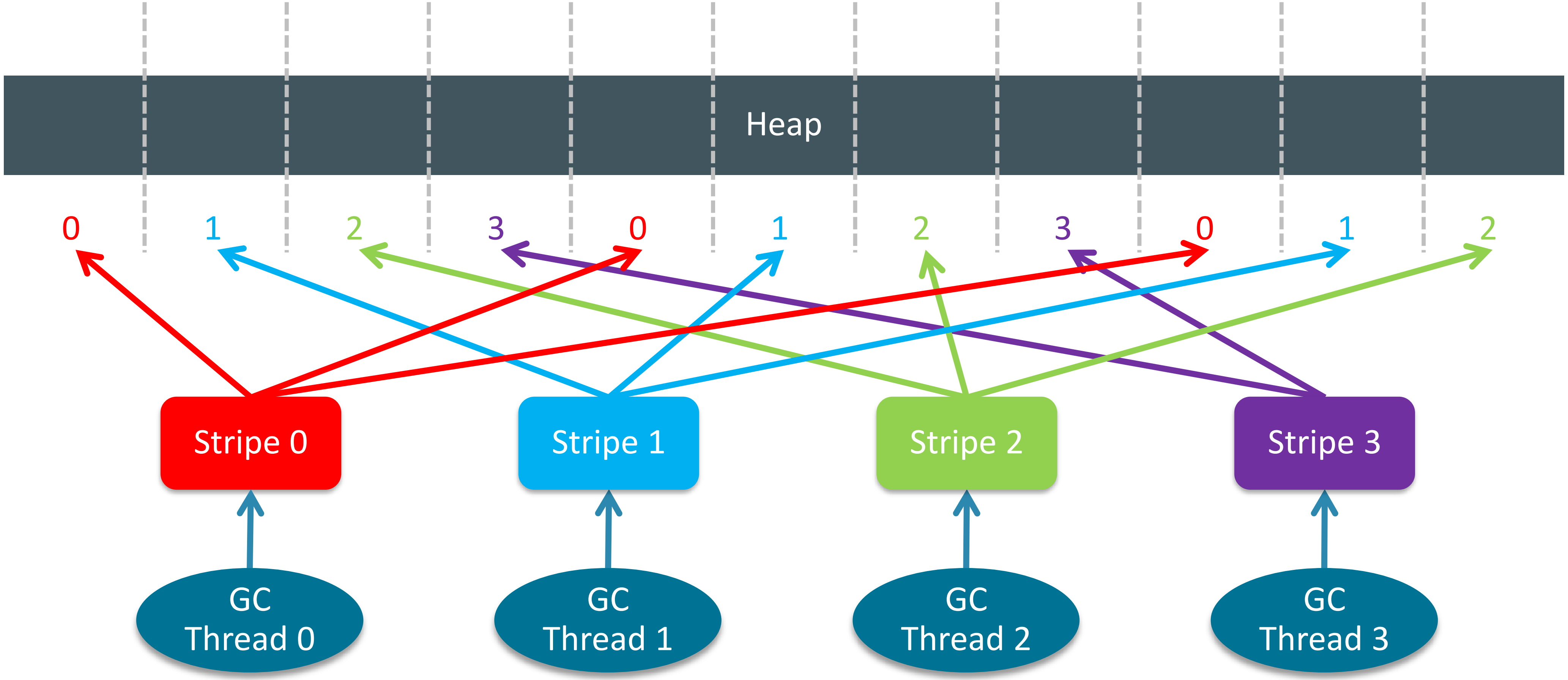
Striped Mark



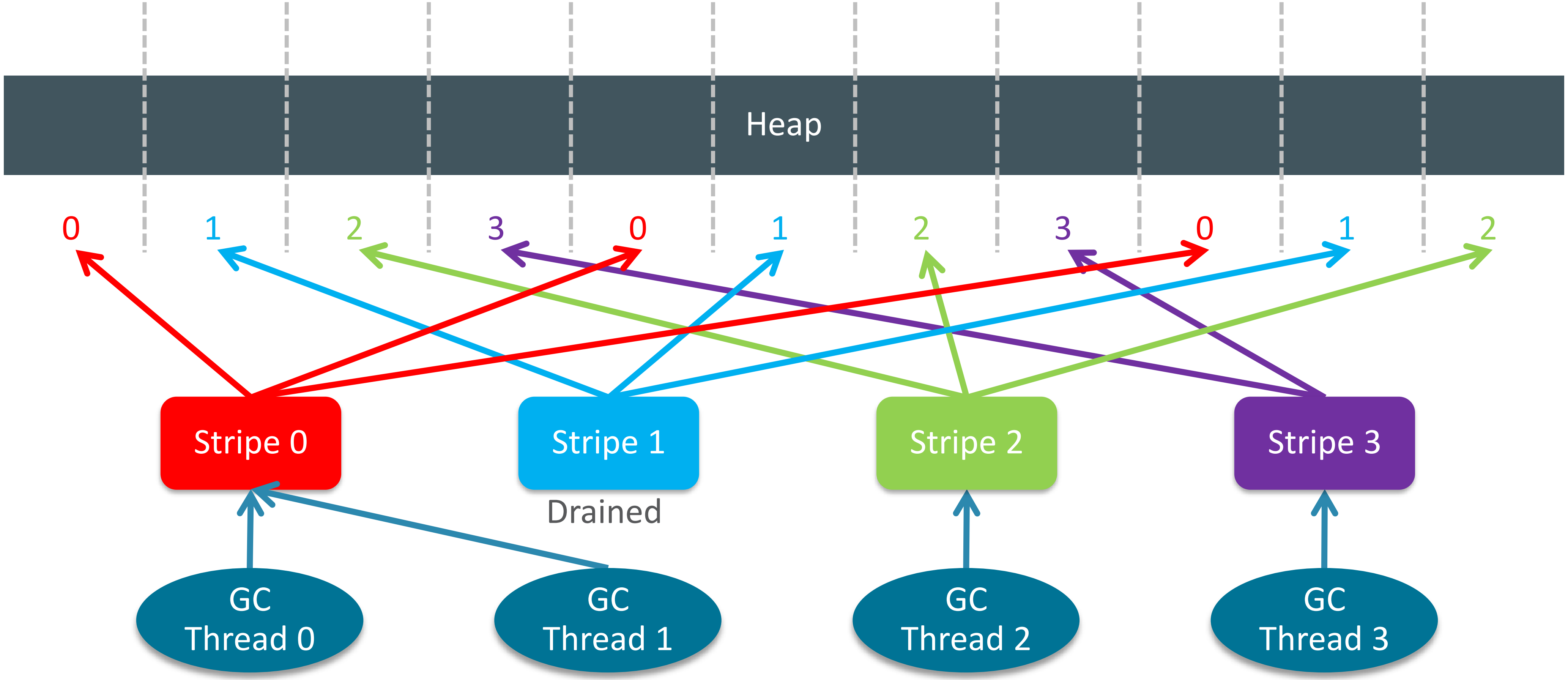
Striped Mark



Striped Mark



Striped Mark

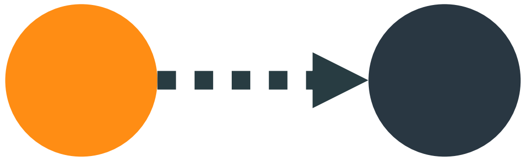


Reference Processing

Dealing with Soft/Weak/Final/PhantomReference

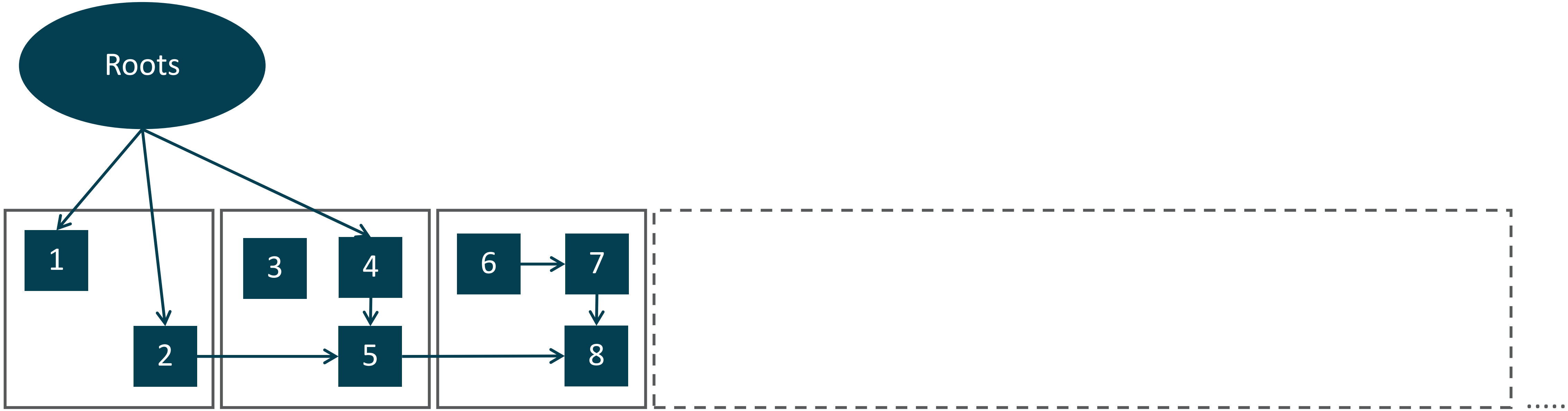
- Concurrent & Parallel
- Liveness/Reachability analysis
  - **Complete** after concurrent mark
  - Strongly reachable, Final reachable and Unreachable
- Processing/Enqueuing
  - **Single** pass
  - Load barrier **blocks** resurrection attempts (e.g. through **`Reference.get()`**)

Relocation

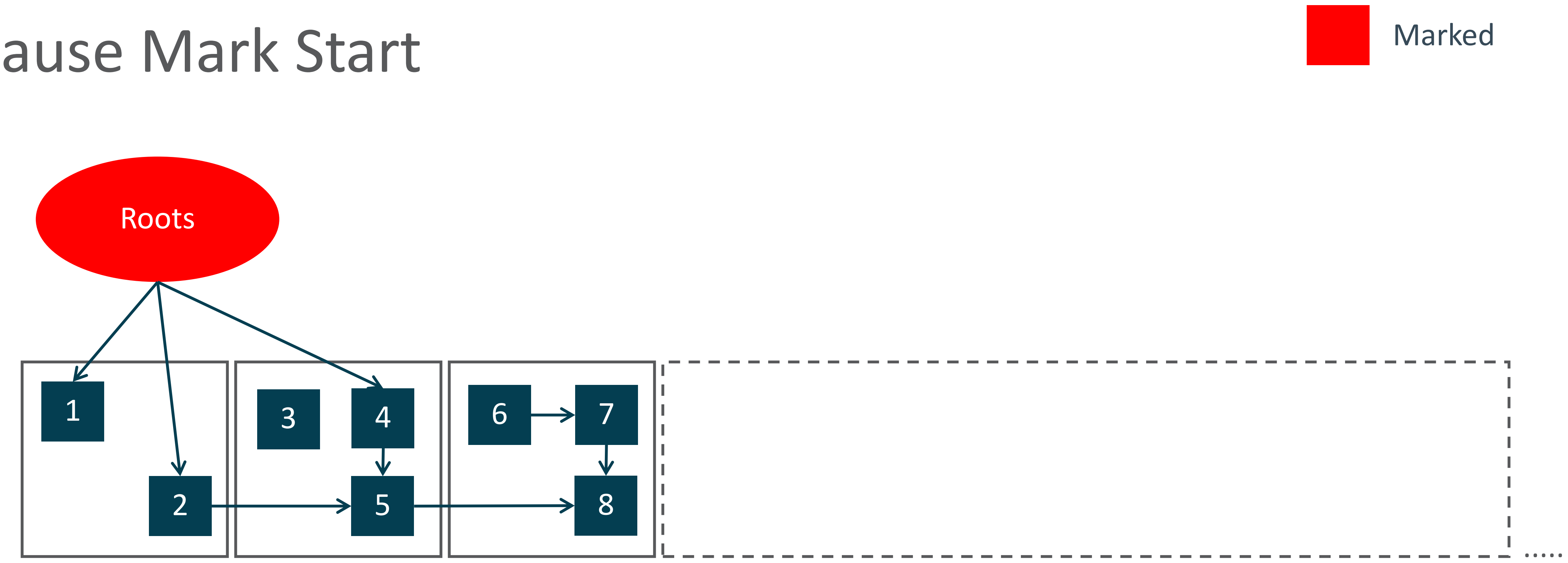


- Concurrent & Parallel
- Load barrier
  - Detects loads of object pointers pointing into the relocation set
  - Java threads help out with relocation if needed
- Off-heap forwarding tables
  - No forwarding information stored in old copies of objects
  - Important for immediate reuse of heap memory

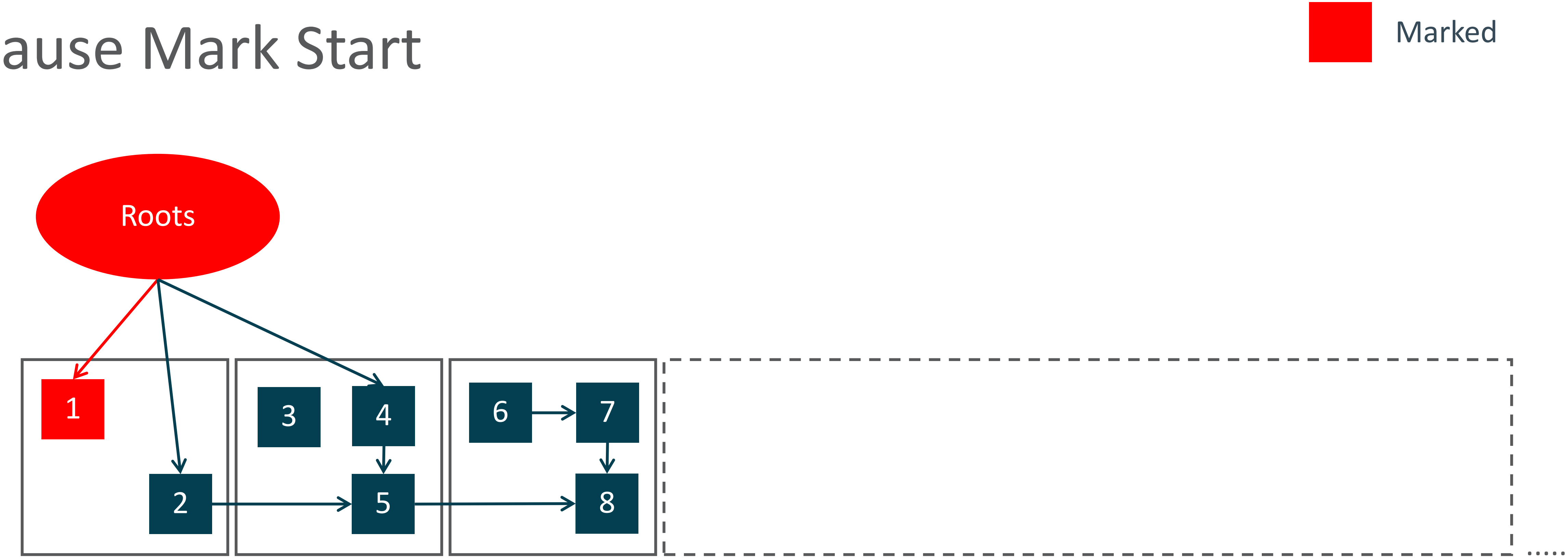
GC Cycle Example



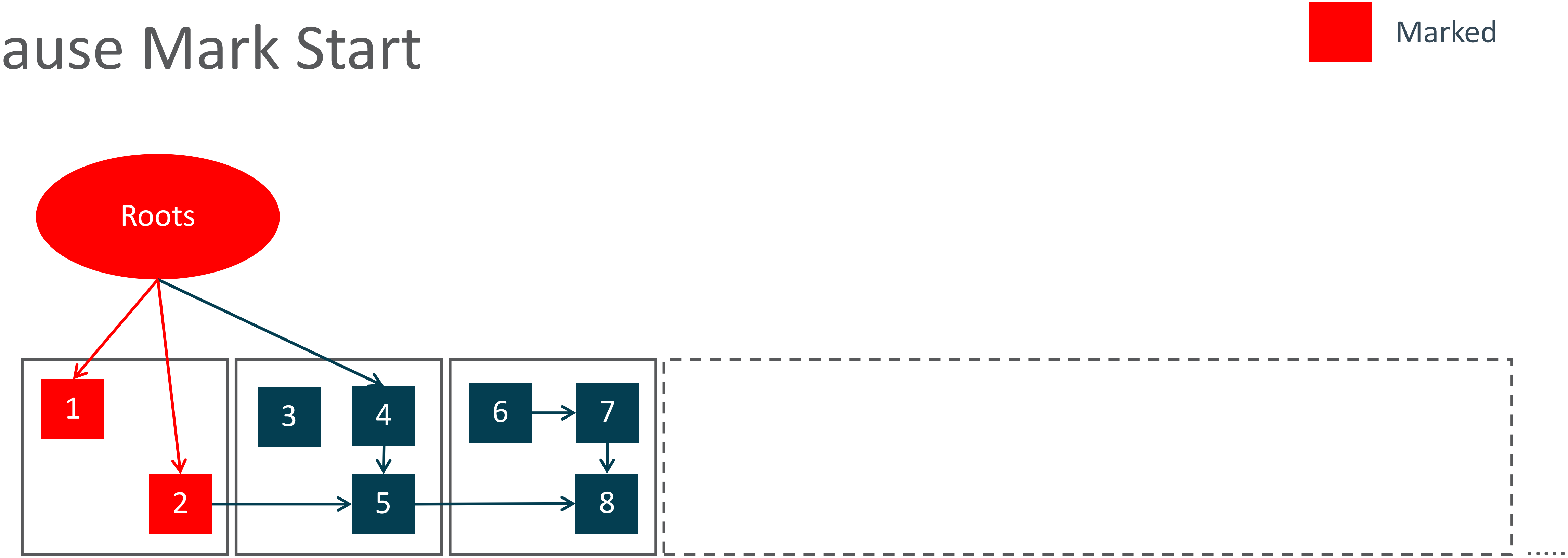
Pause Mark Start



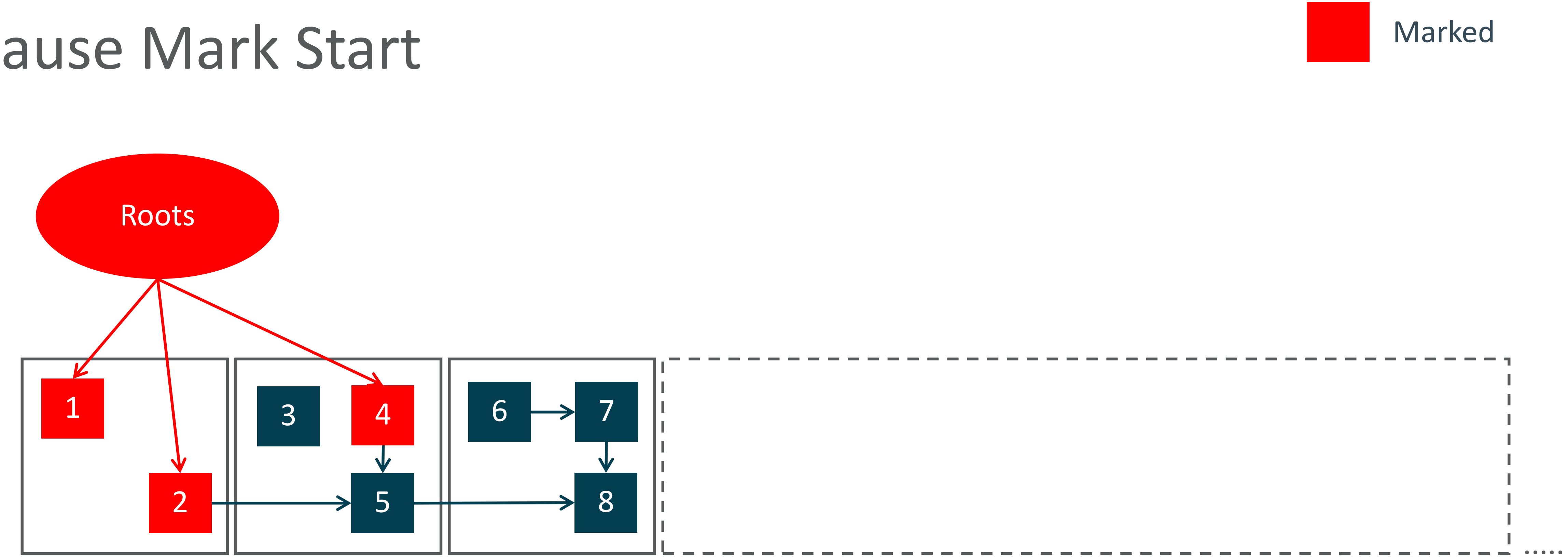
Pause Mark Start



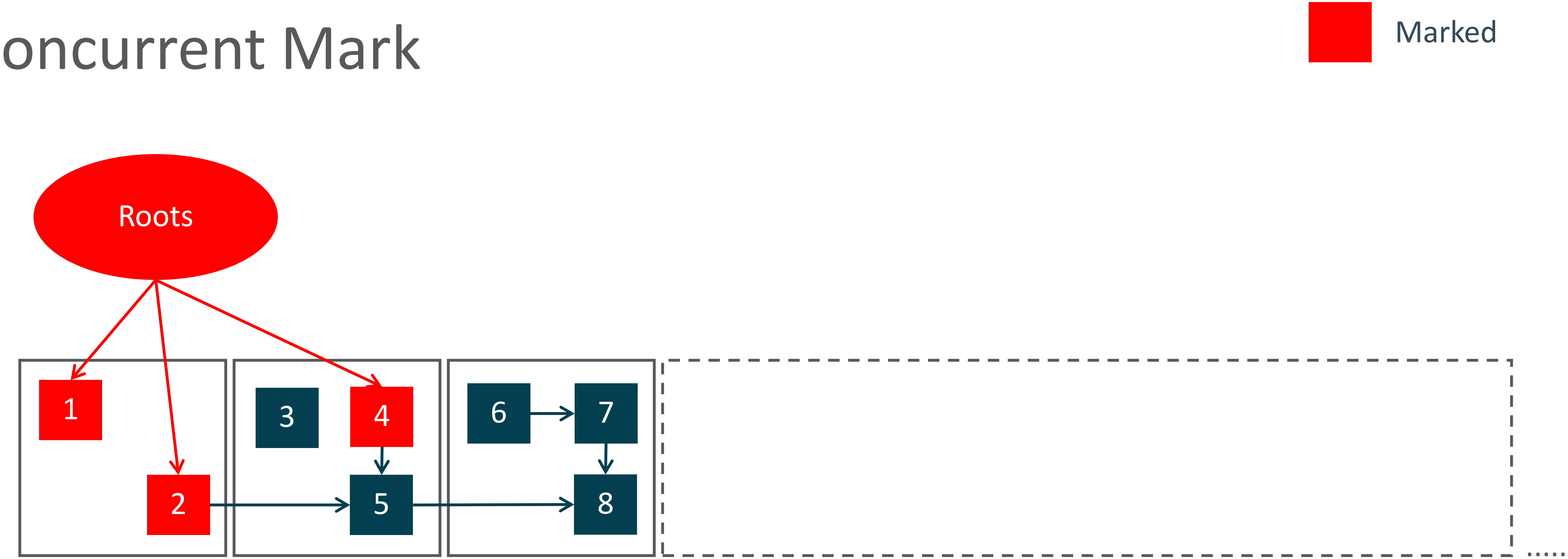
Pause Mark Start



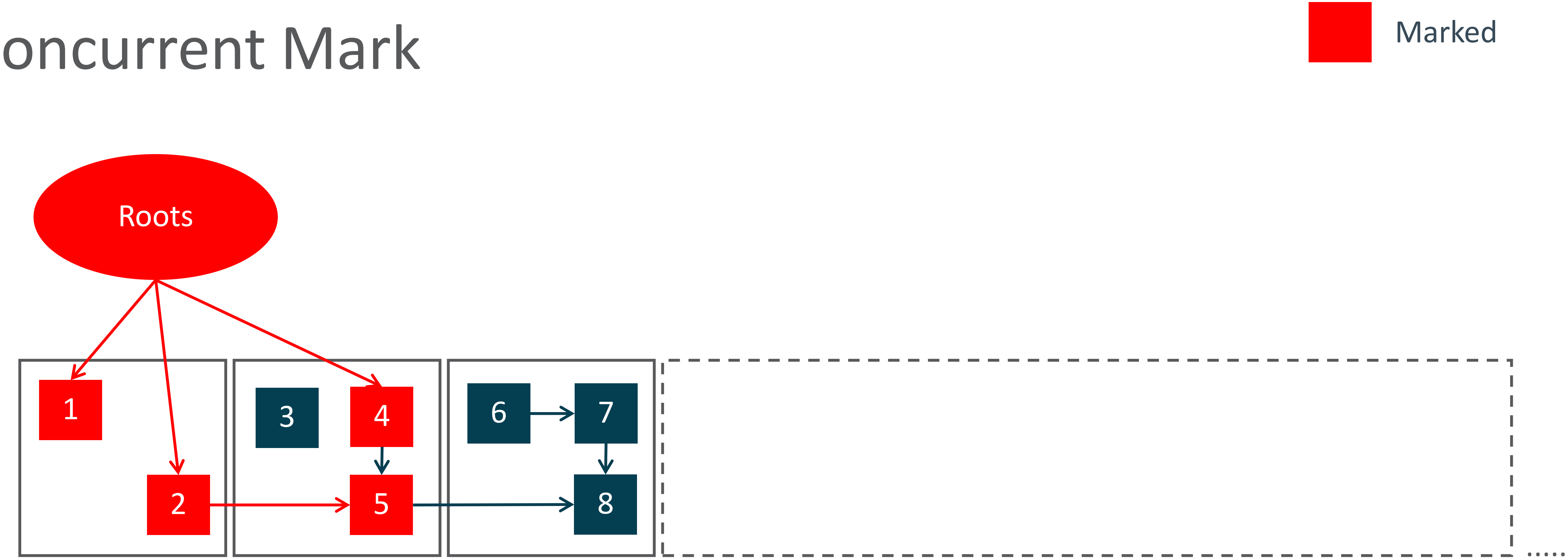
Pause Mark Start



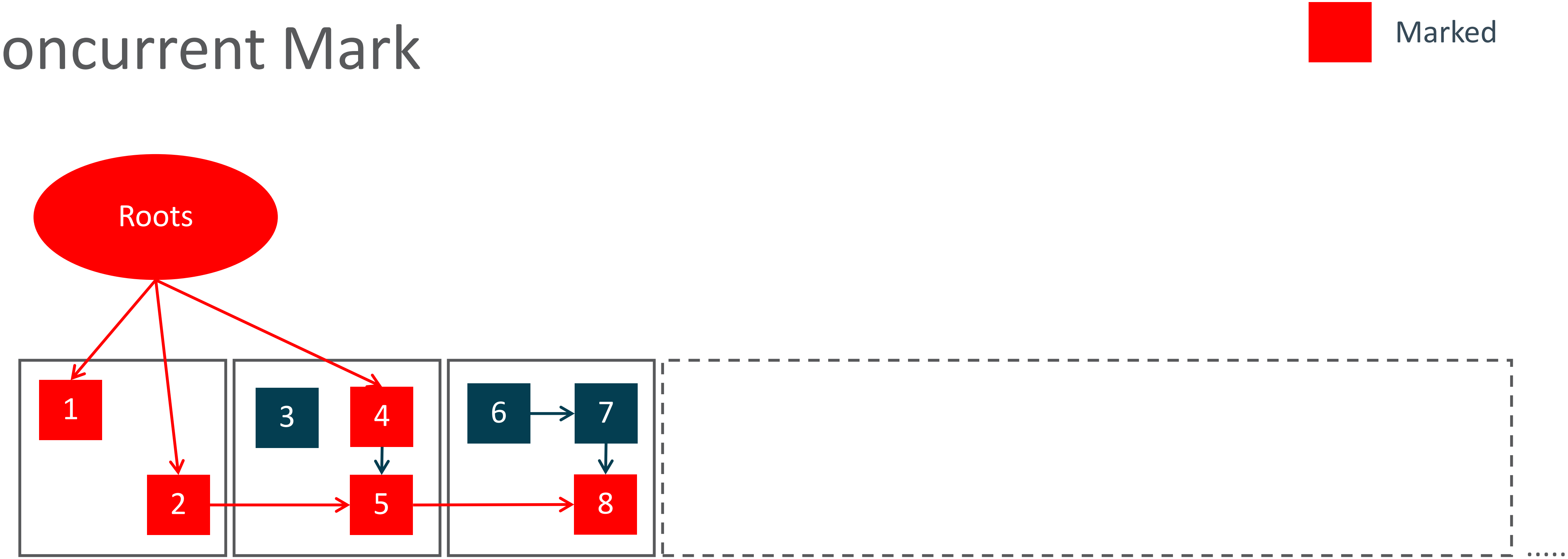
Concurrent Mark



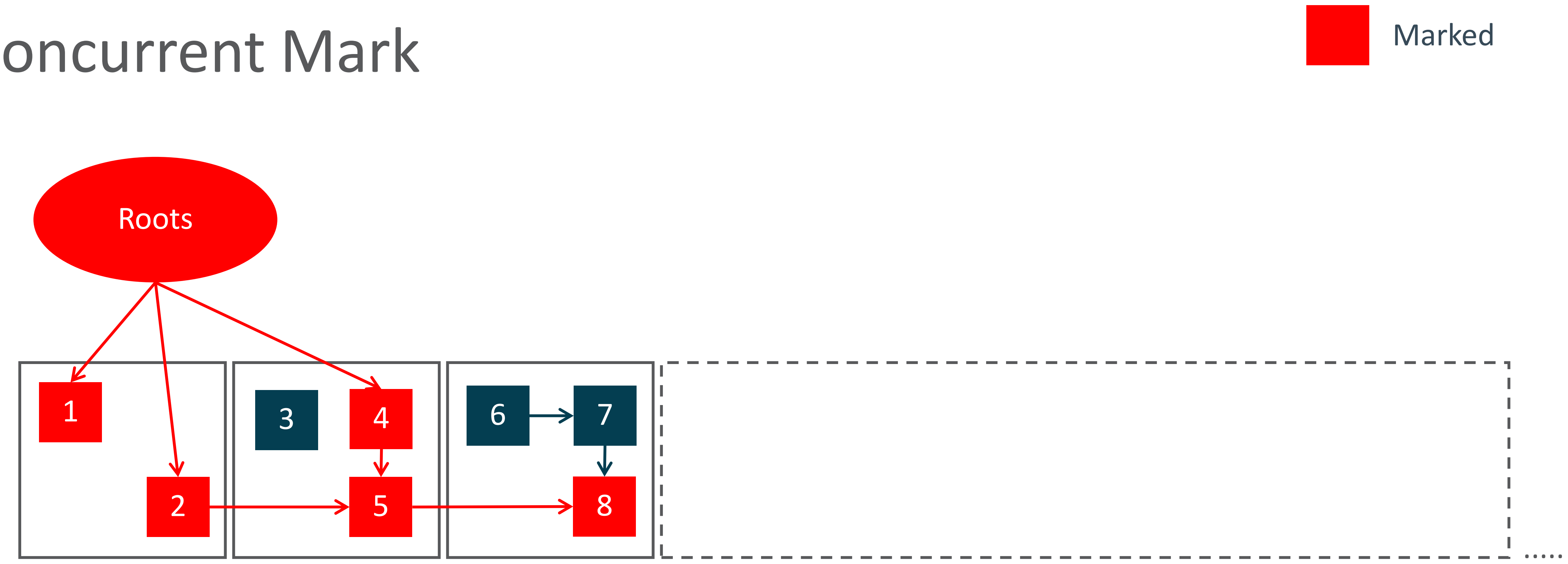
Concurrent Mark



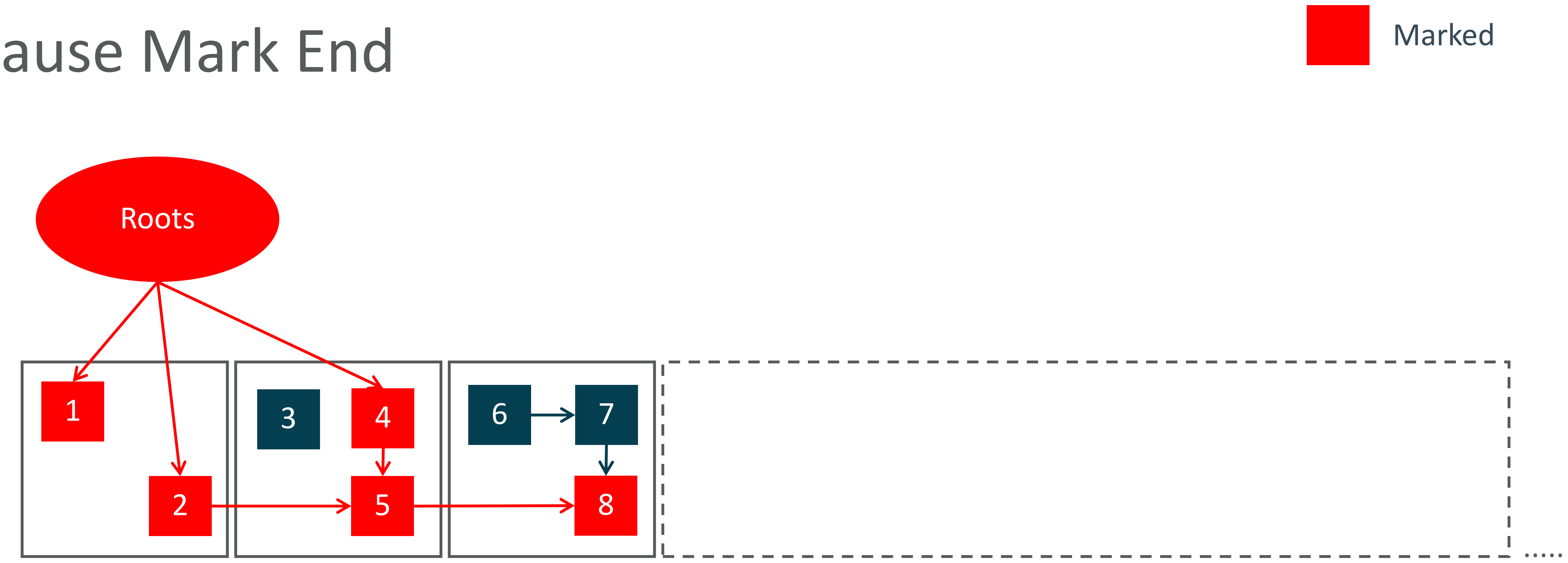
Concurrent Mark



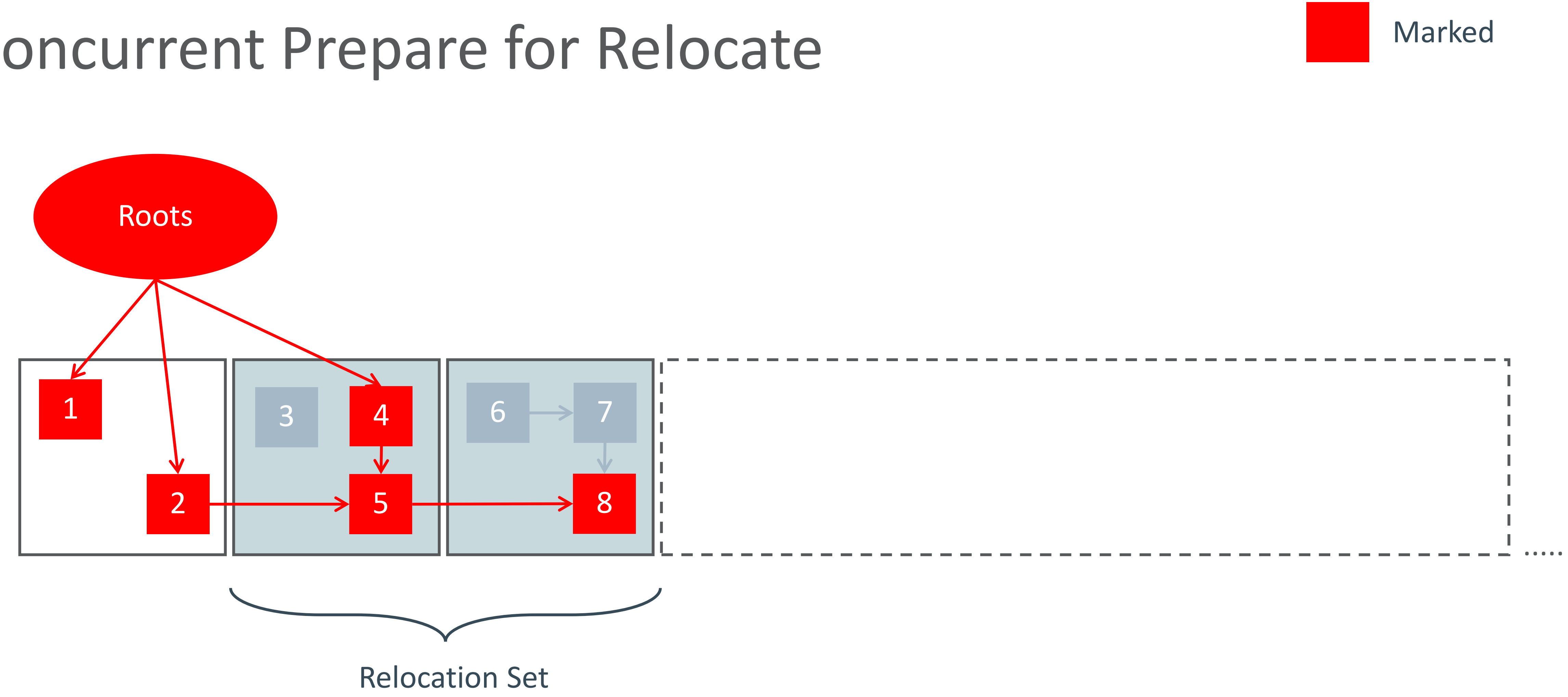
Concurrent Mark



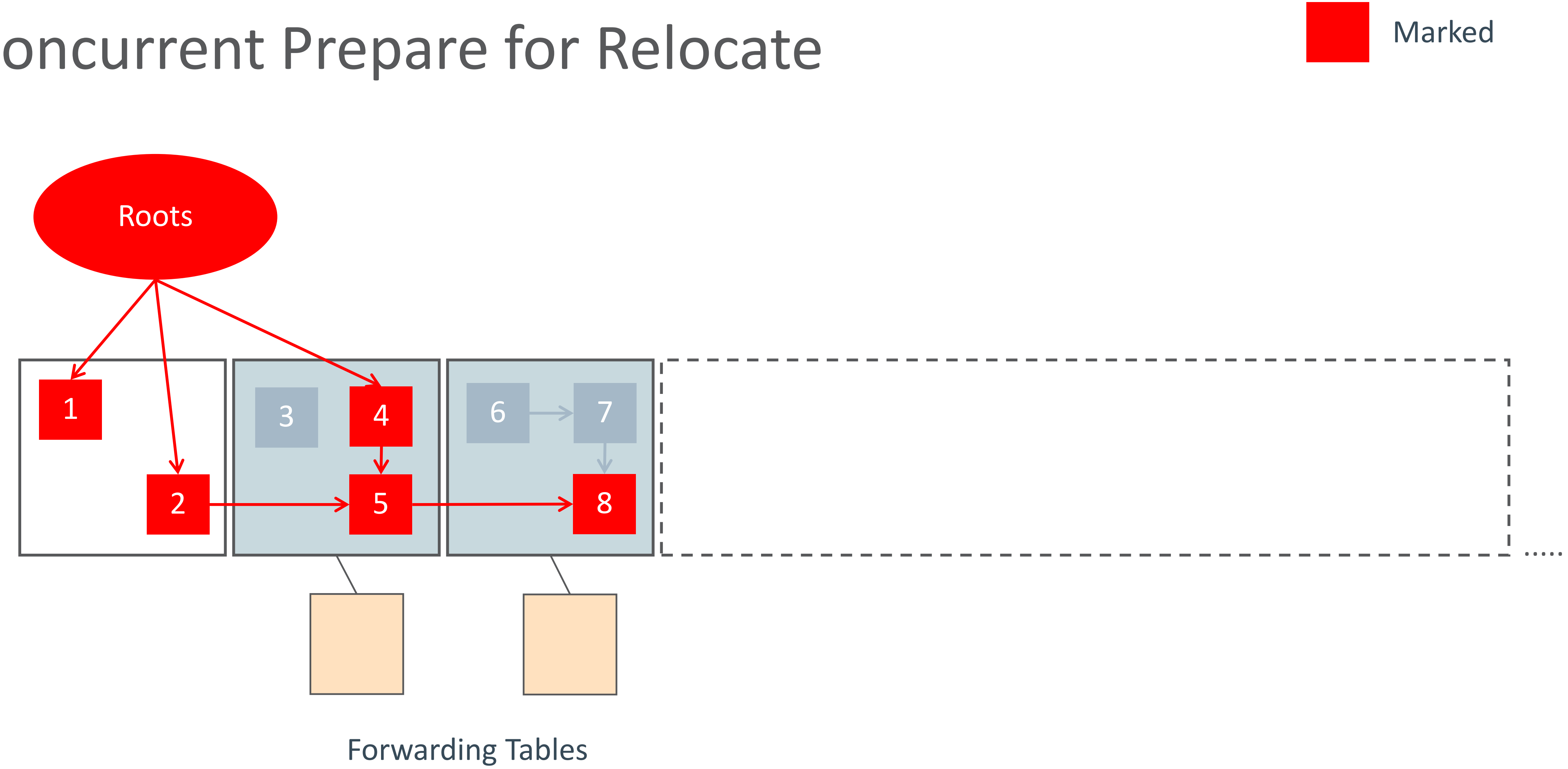
Pause Mark End



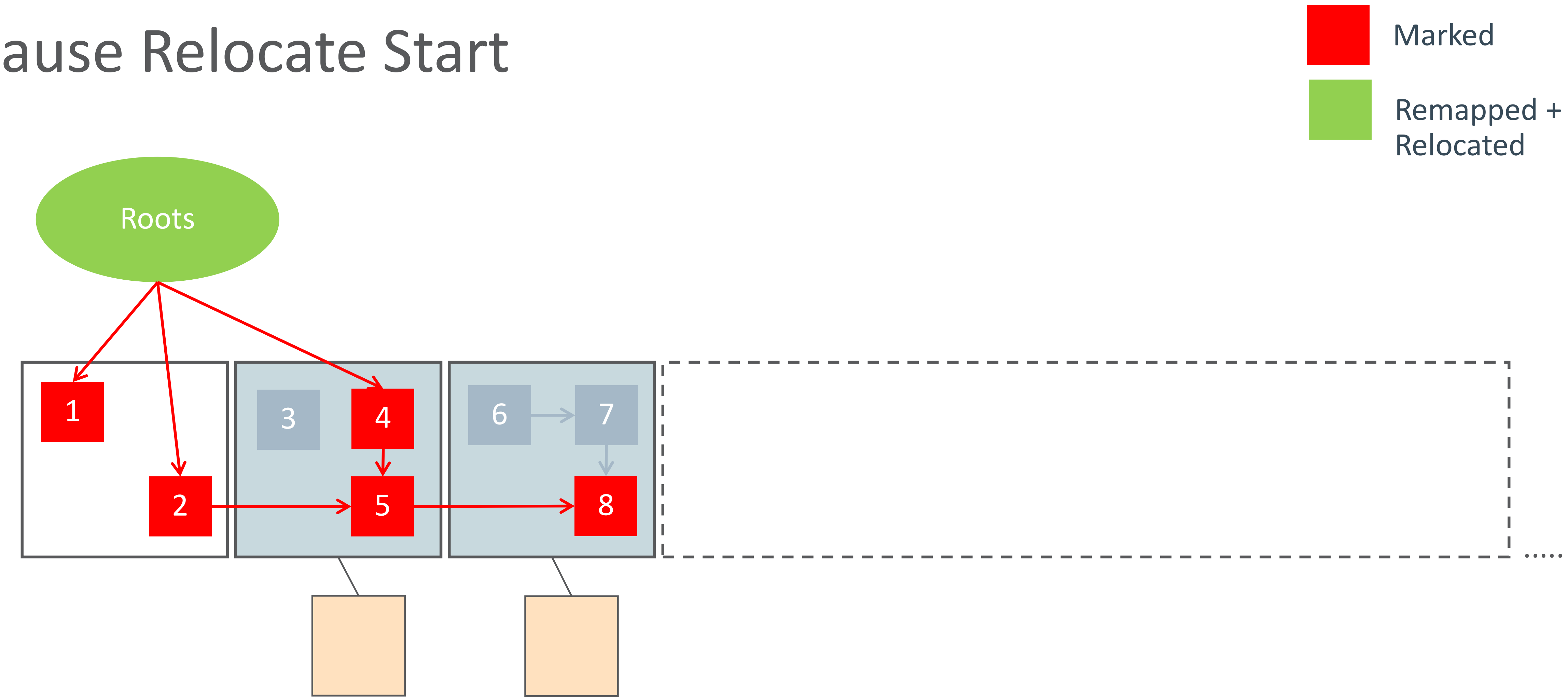
Concurrent Prepare for Relocate



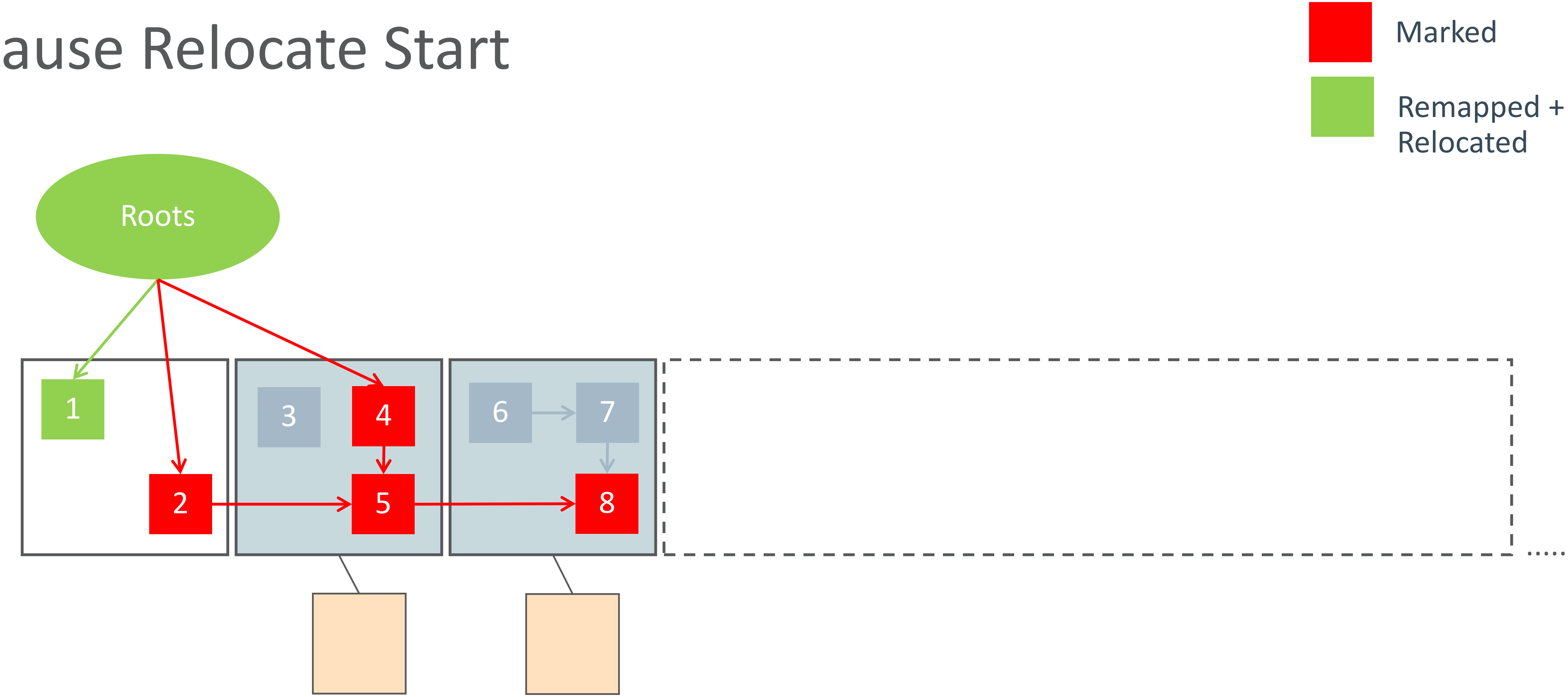
Concurrent Prepare for Relocate



Pause Relocate Start



Pause Relocate Start



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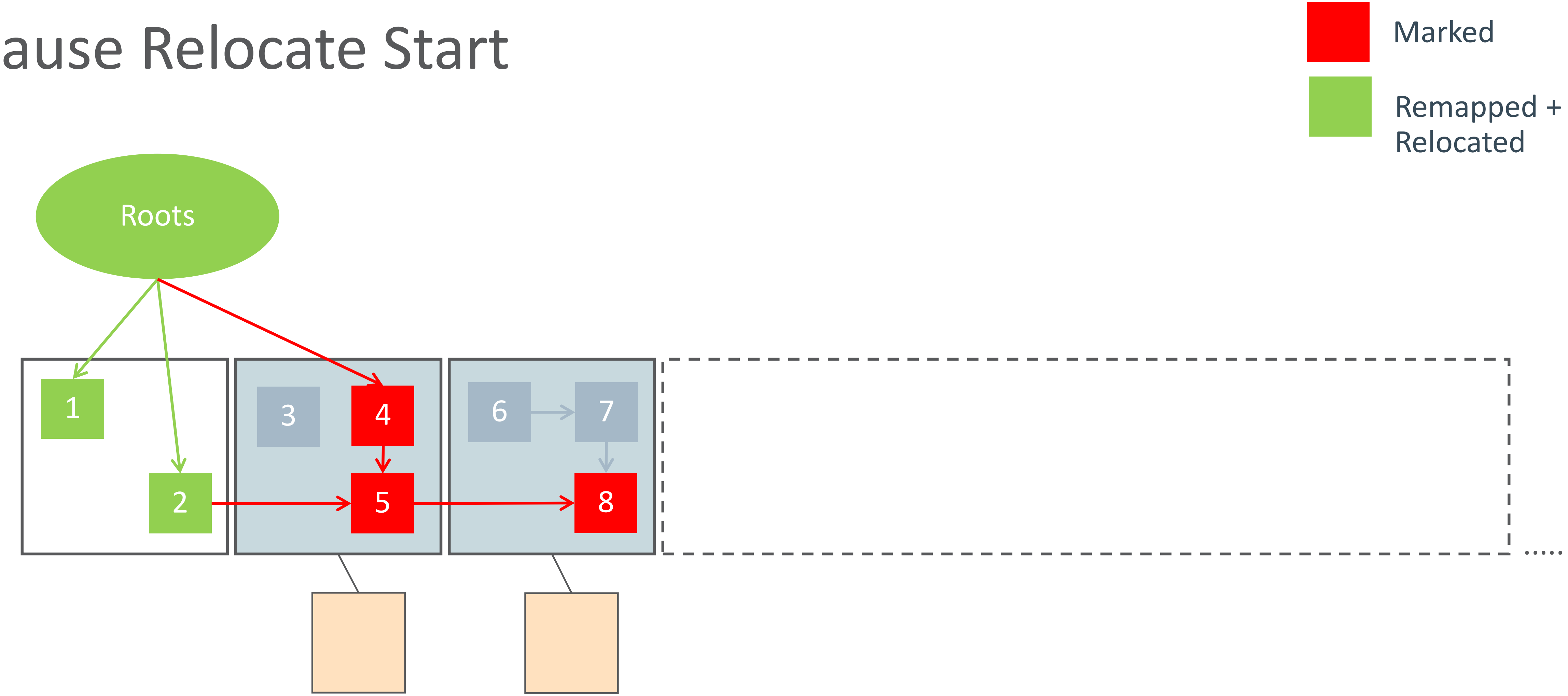

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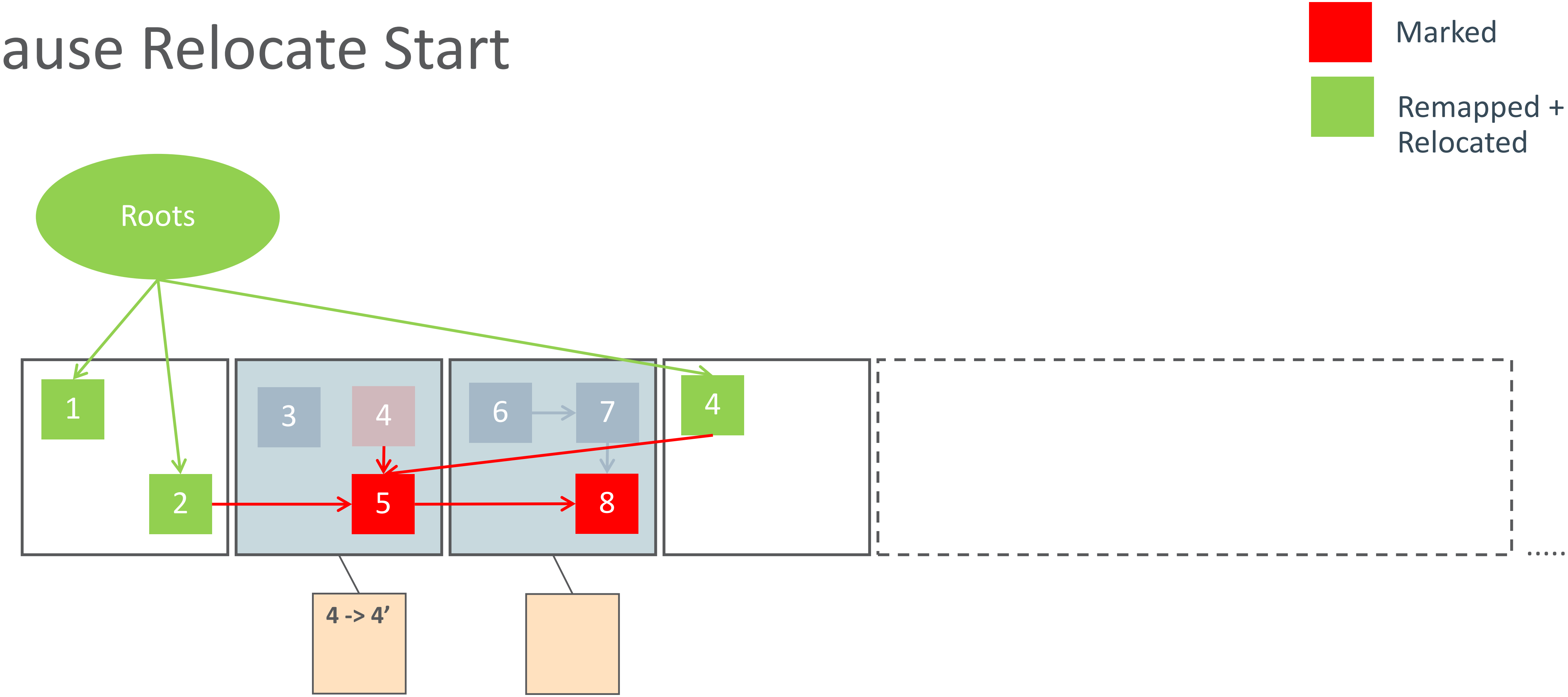
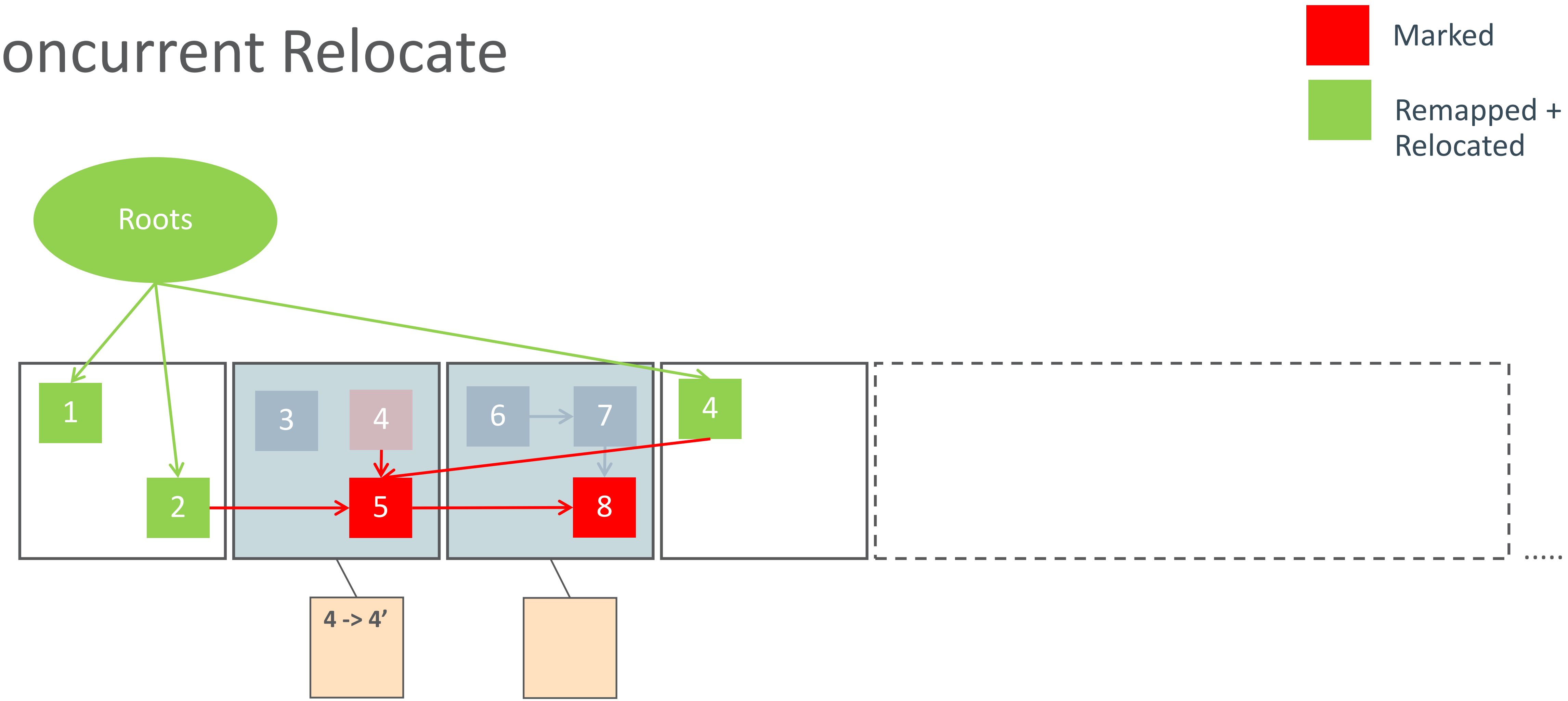
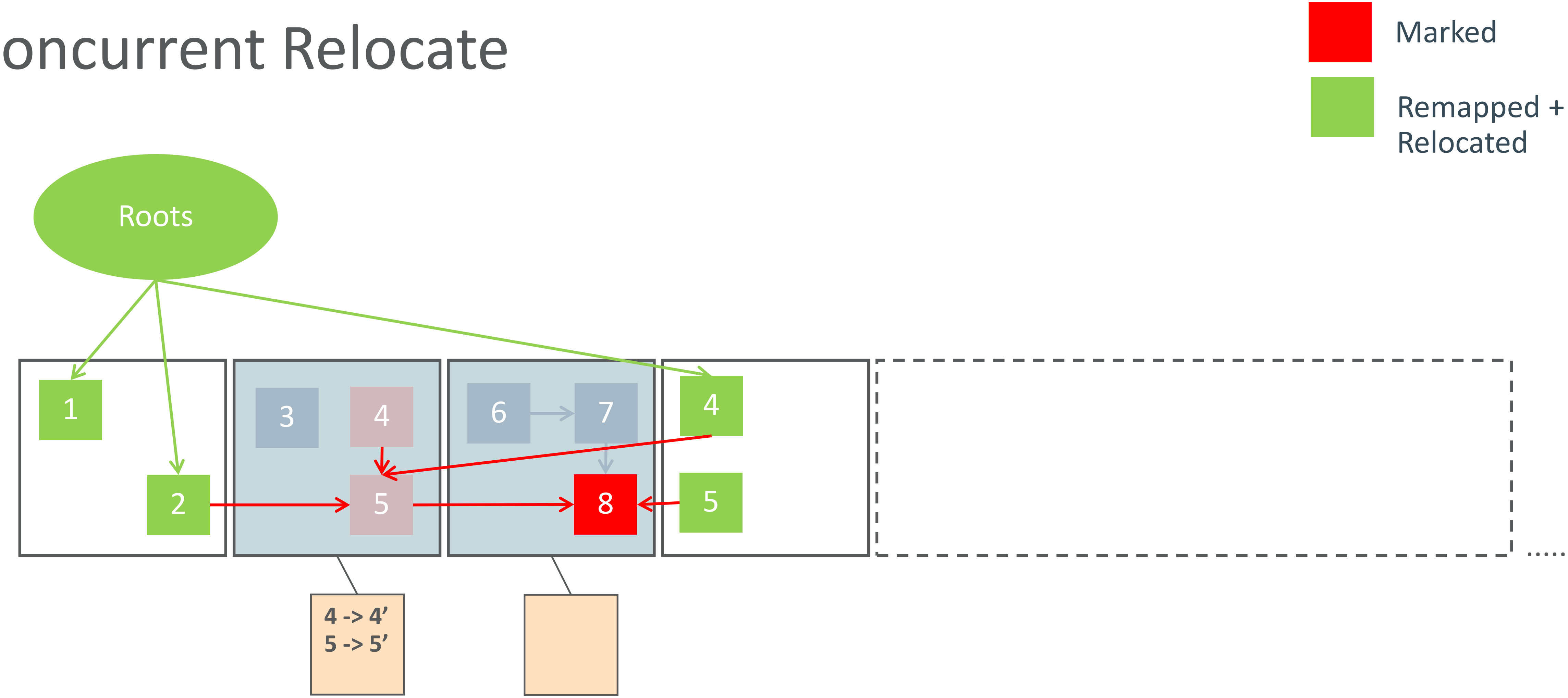


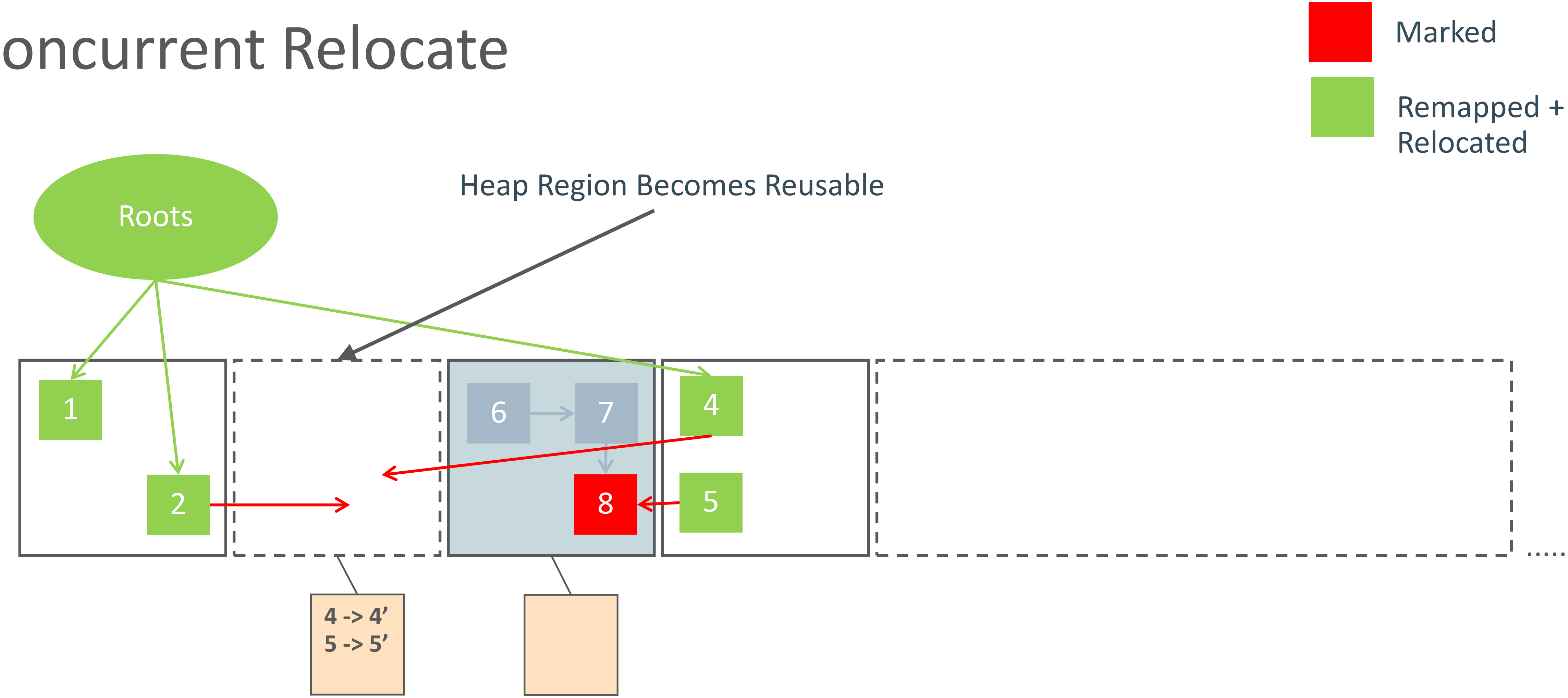
Concurrent Relocate



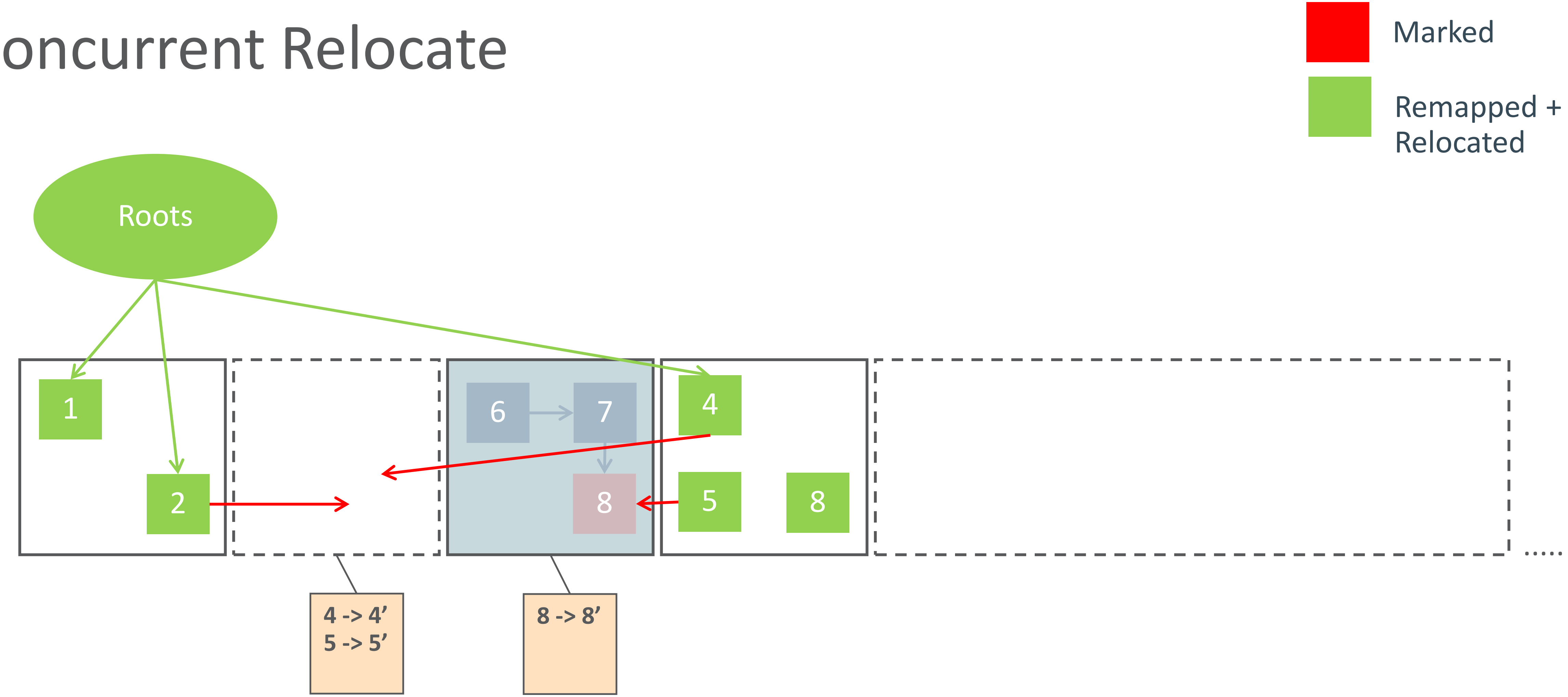
Concurrent Relocate



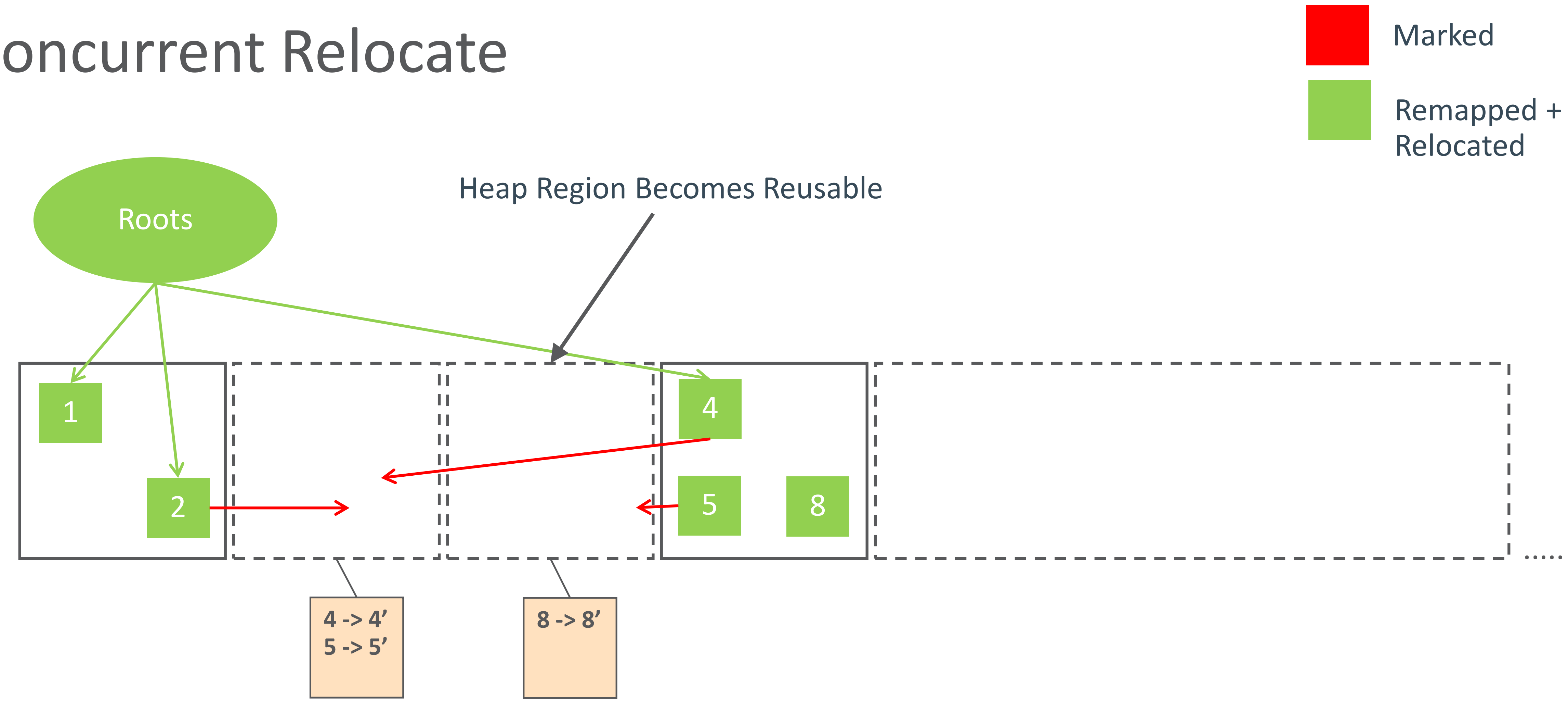
Concurrent Relocate



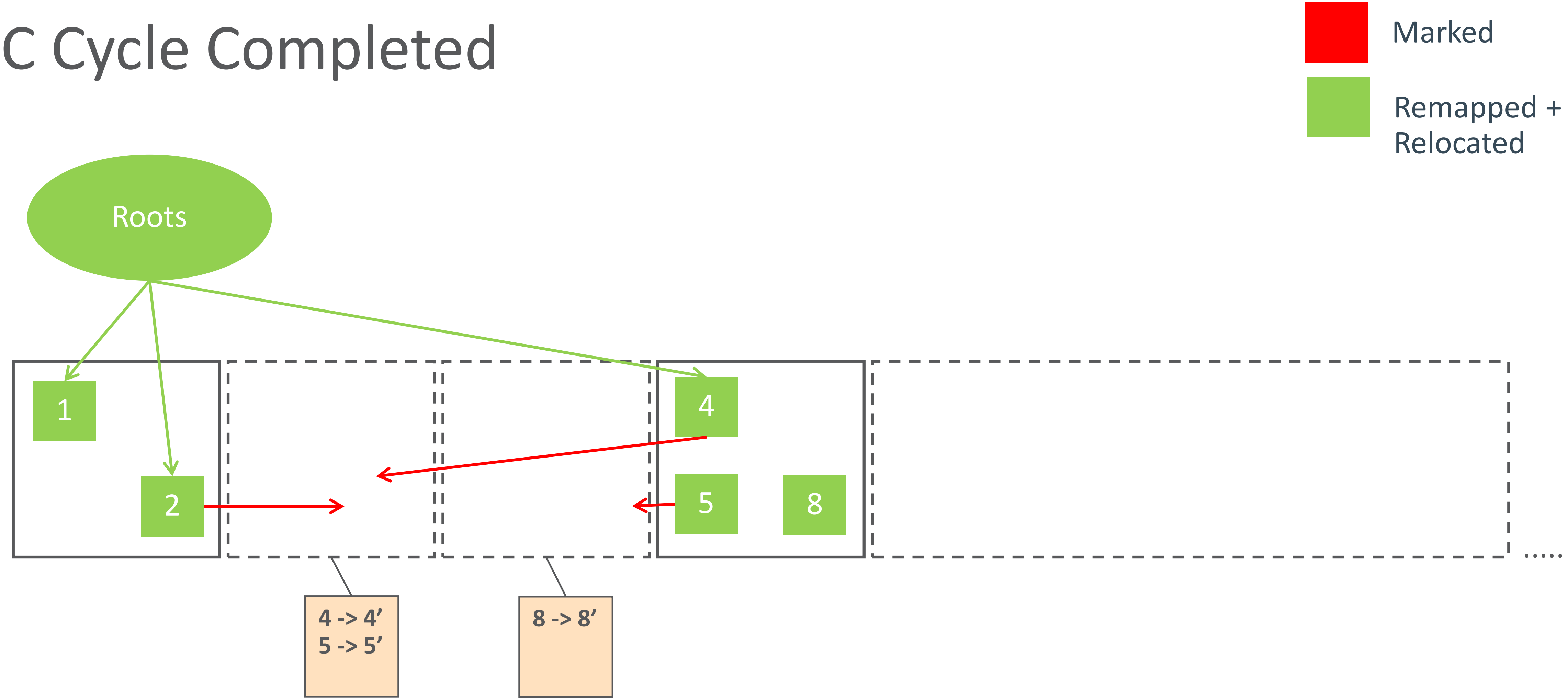
Concurrent Relocate



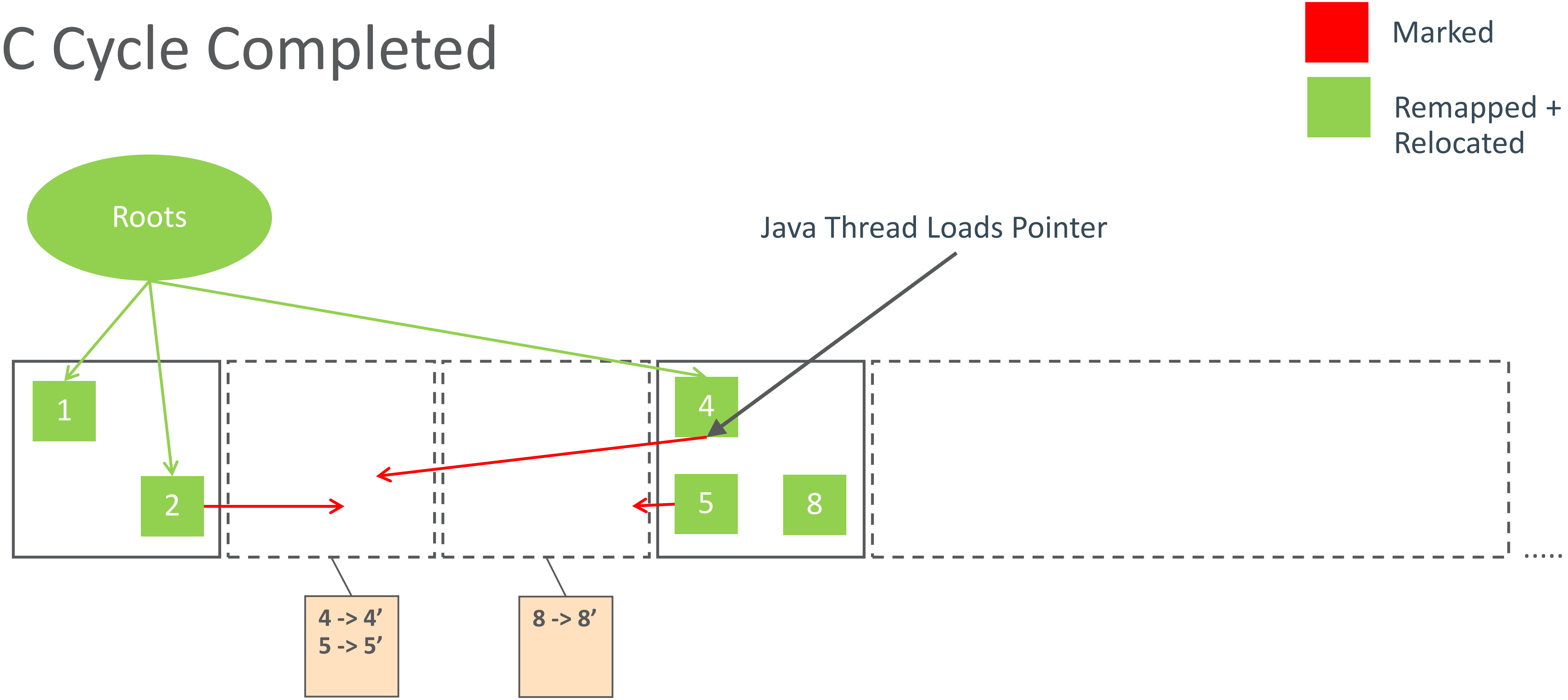
Concurrent Relocate



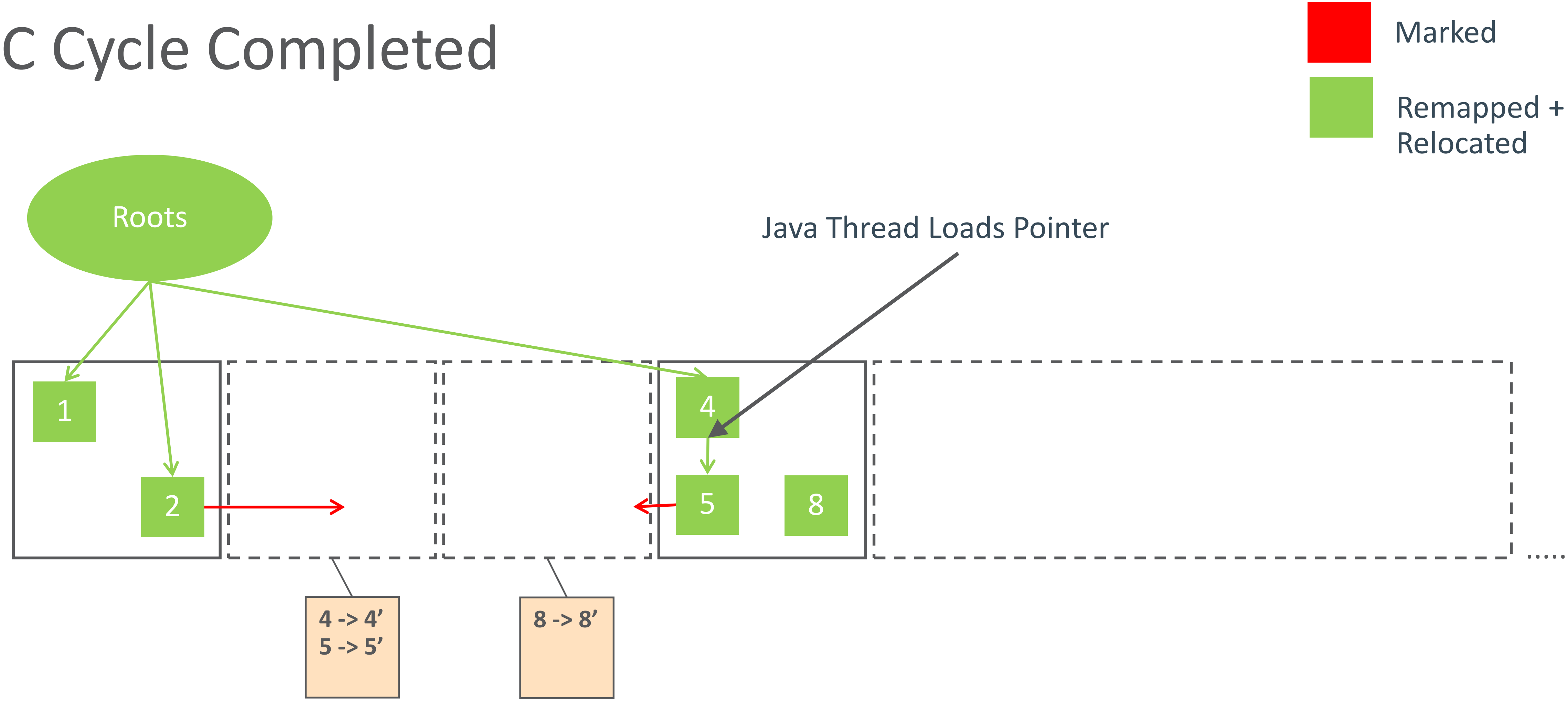
GC Cycle Completed



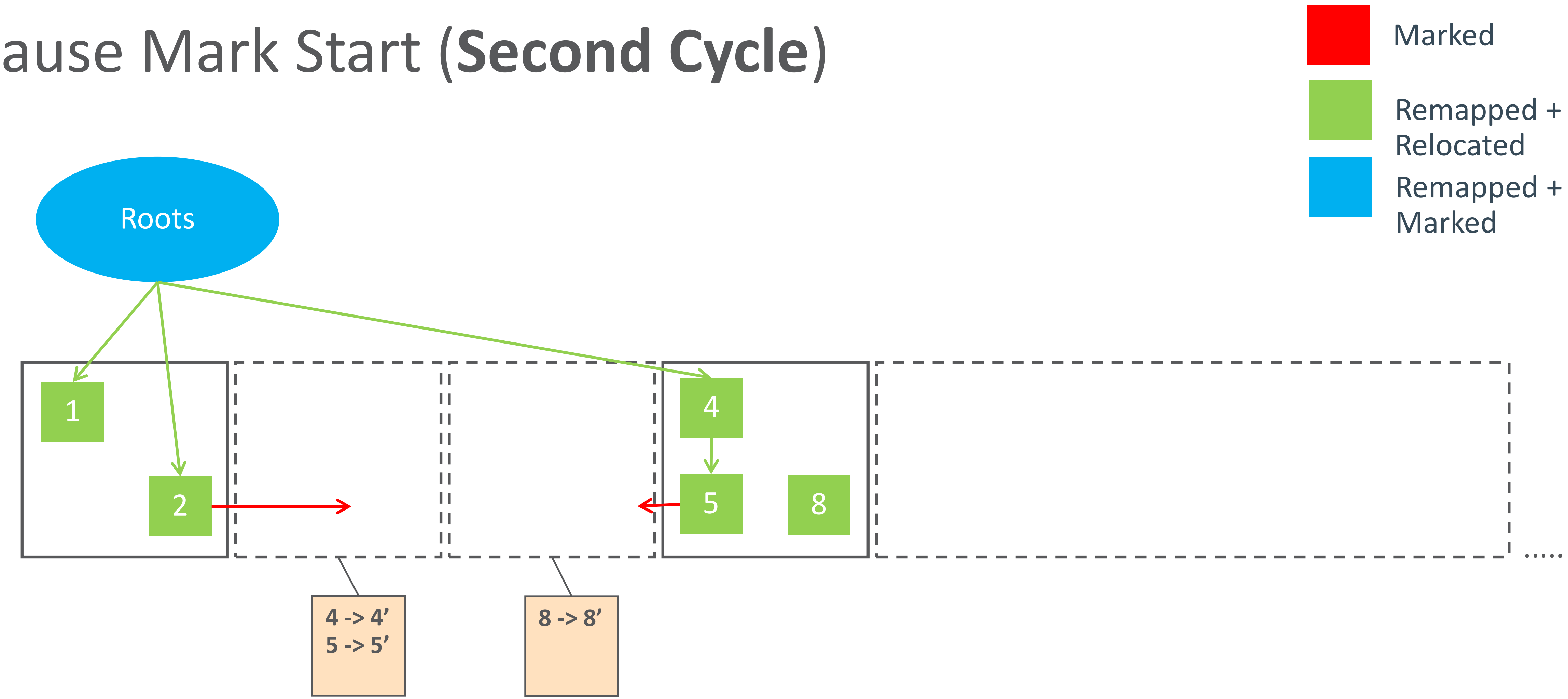
GC Cycle Completed



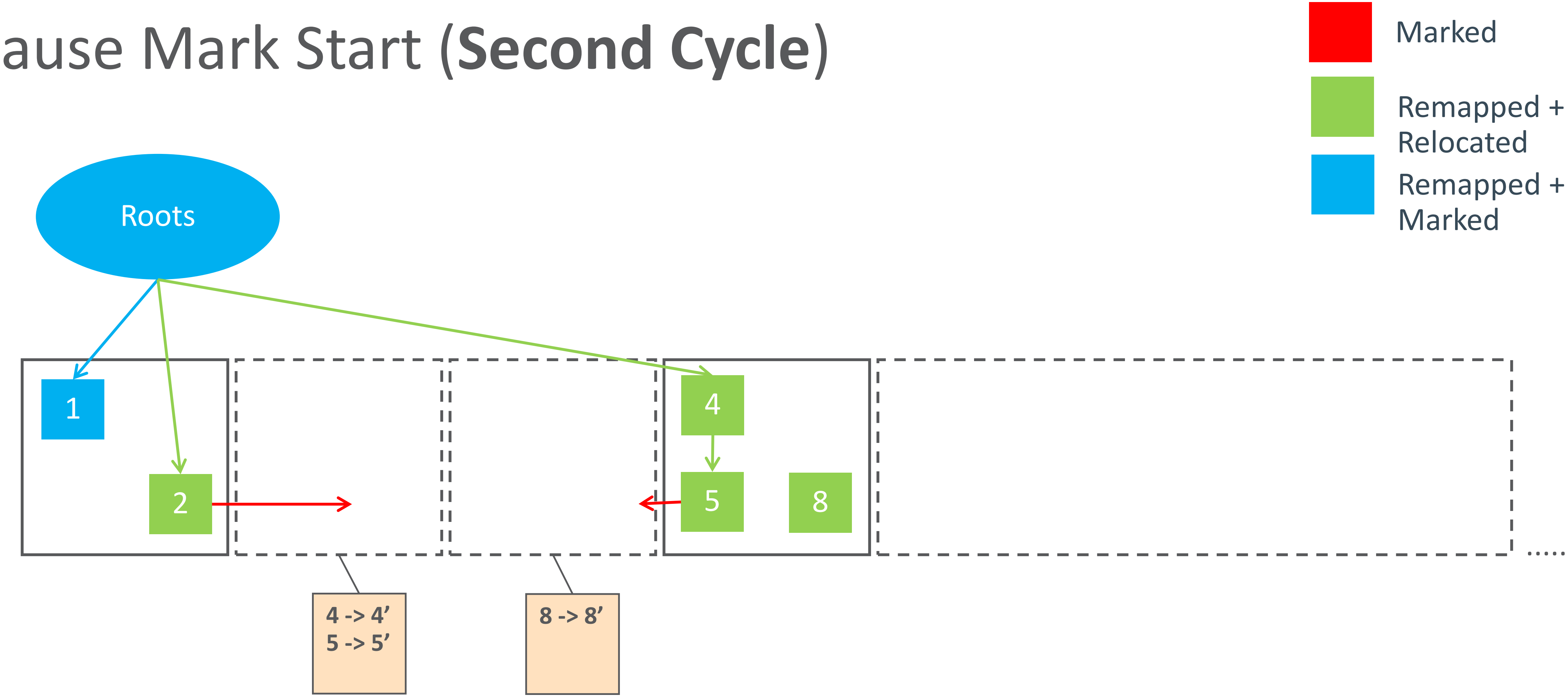
GC Cycle Completed



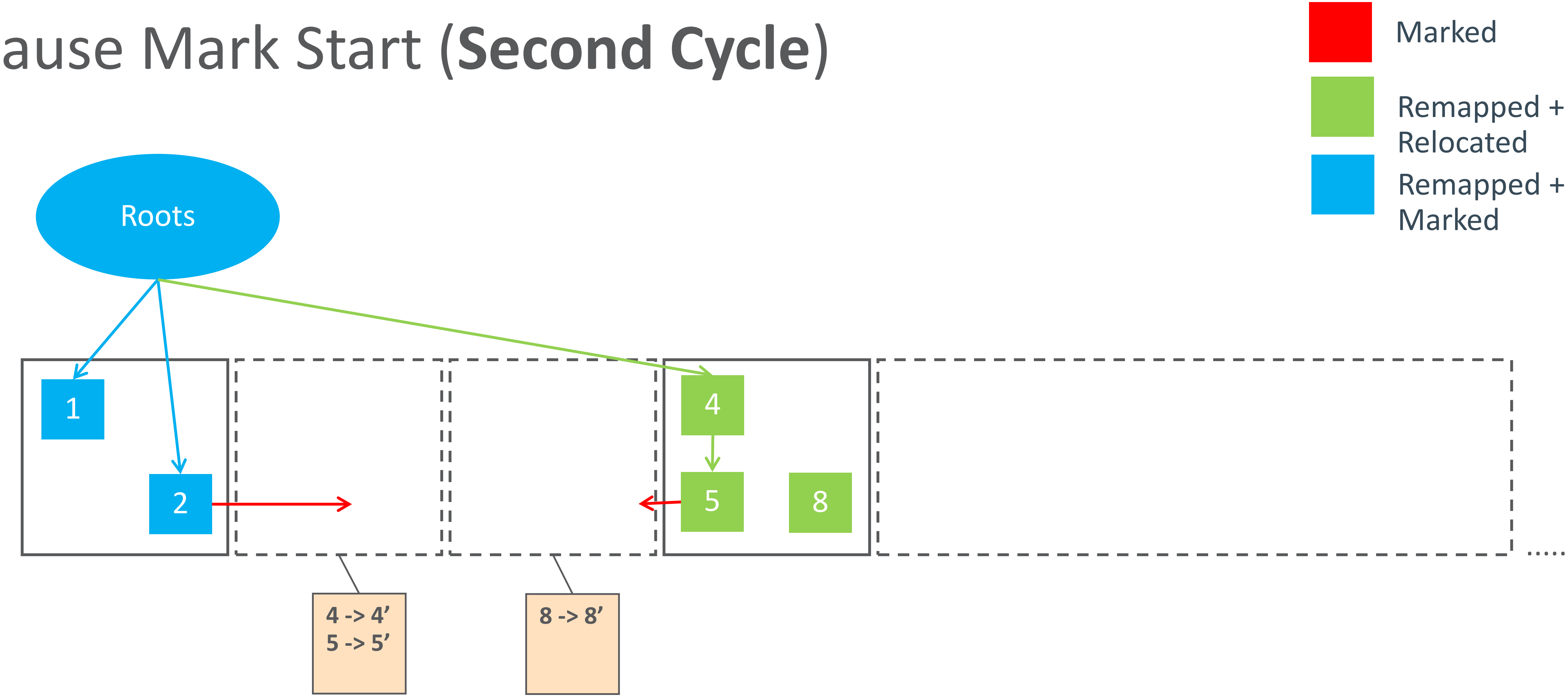
Pause Mark Start (**Second Cycle**)



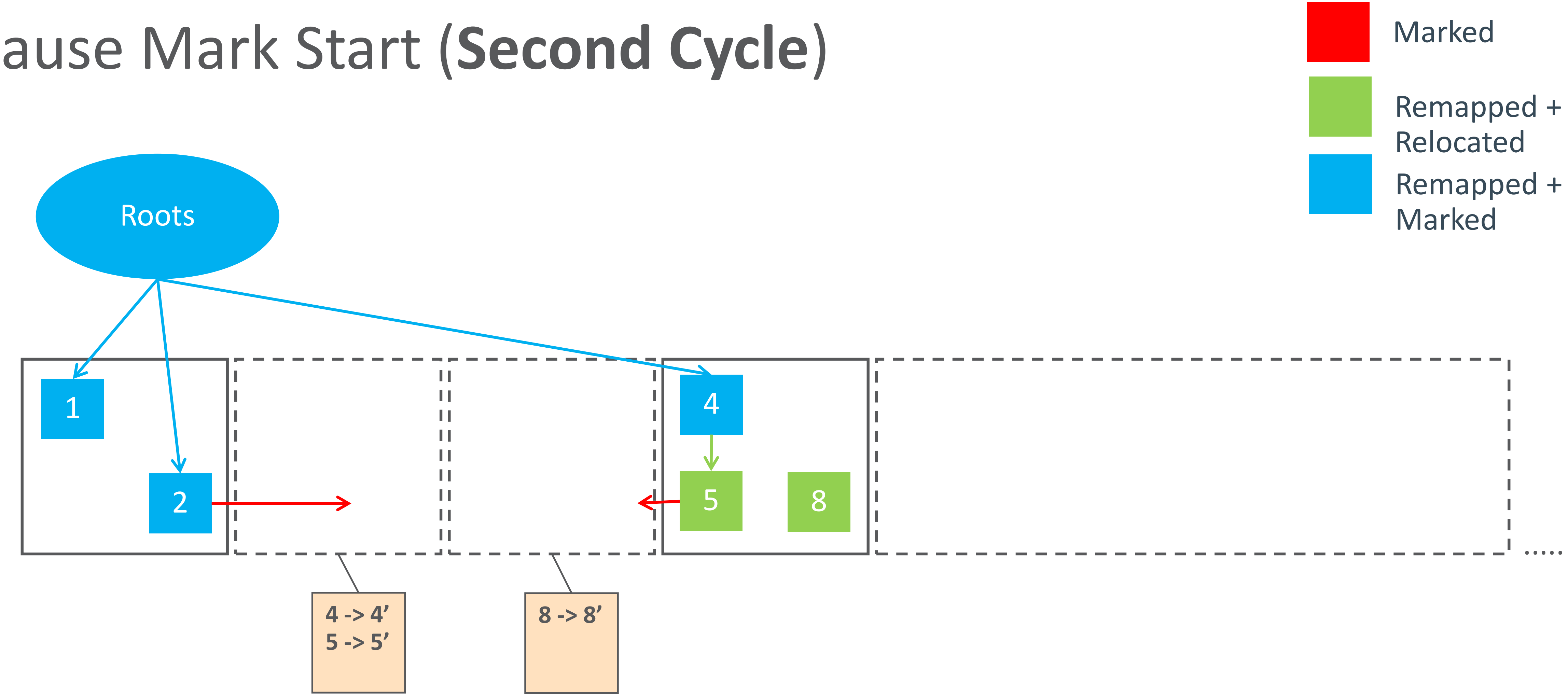
Pause Mark Start (**Second Cycle**)



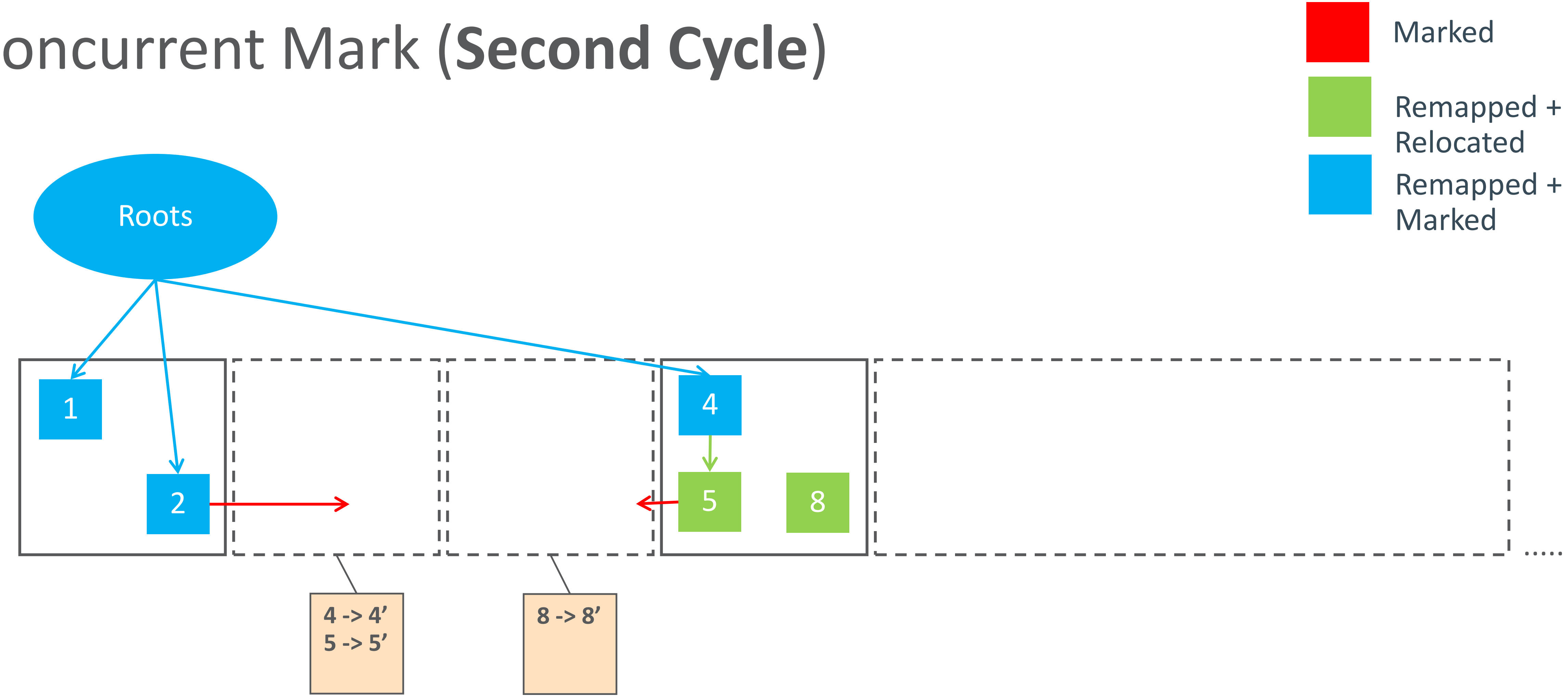
Pause Mark Start (**Second Cycle**)



Pause Mark Start (**Second Cycle**)



Concurrent Mark (**Second Cycle**)

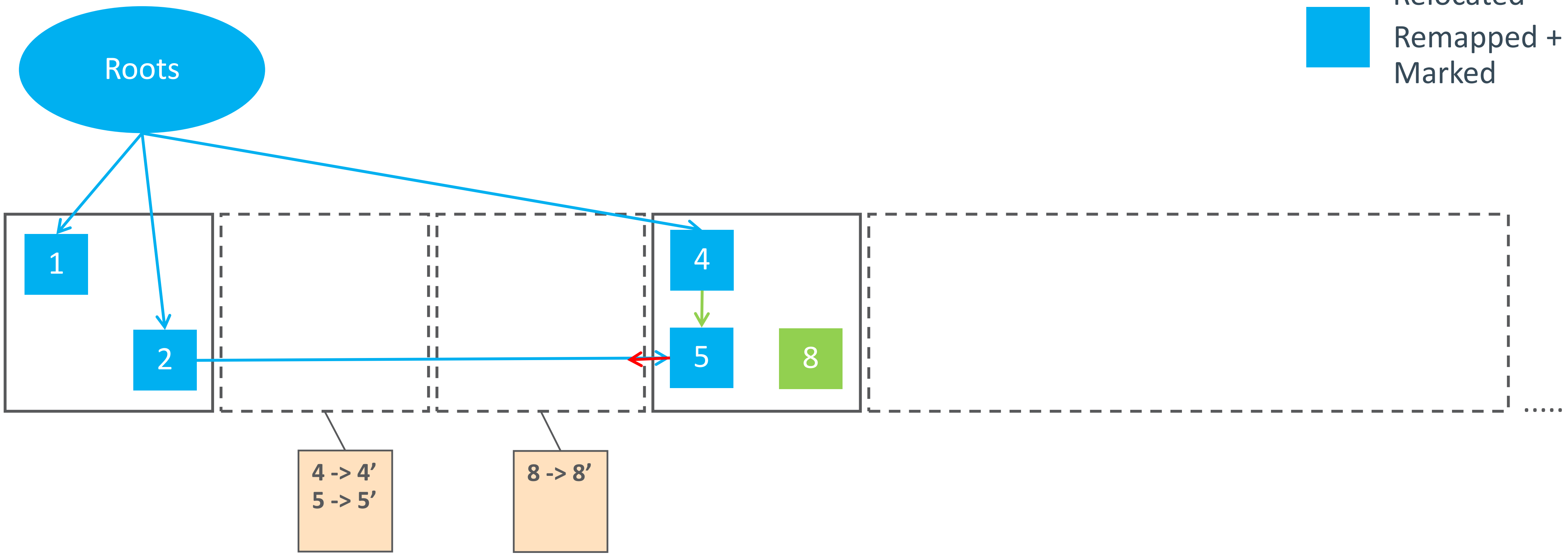


Concurrent Mark (**Second Cycle**)

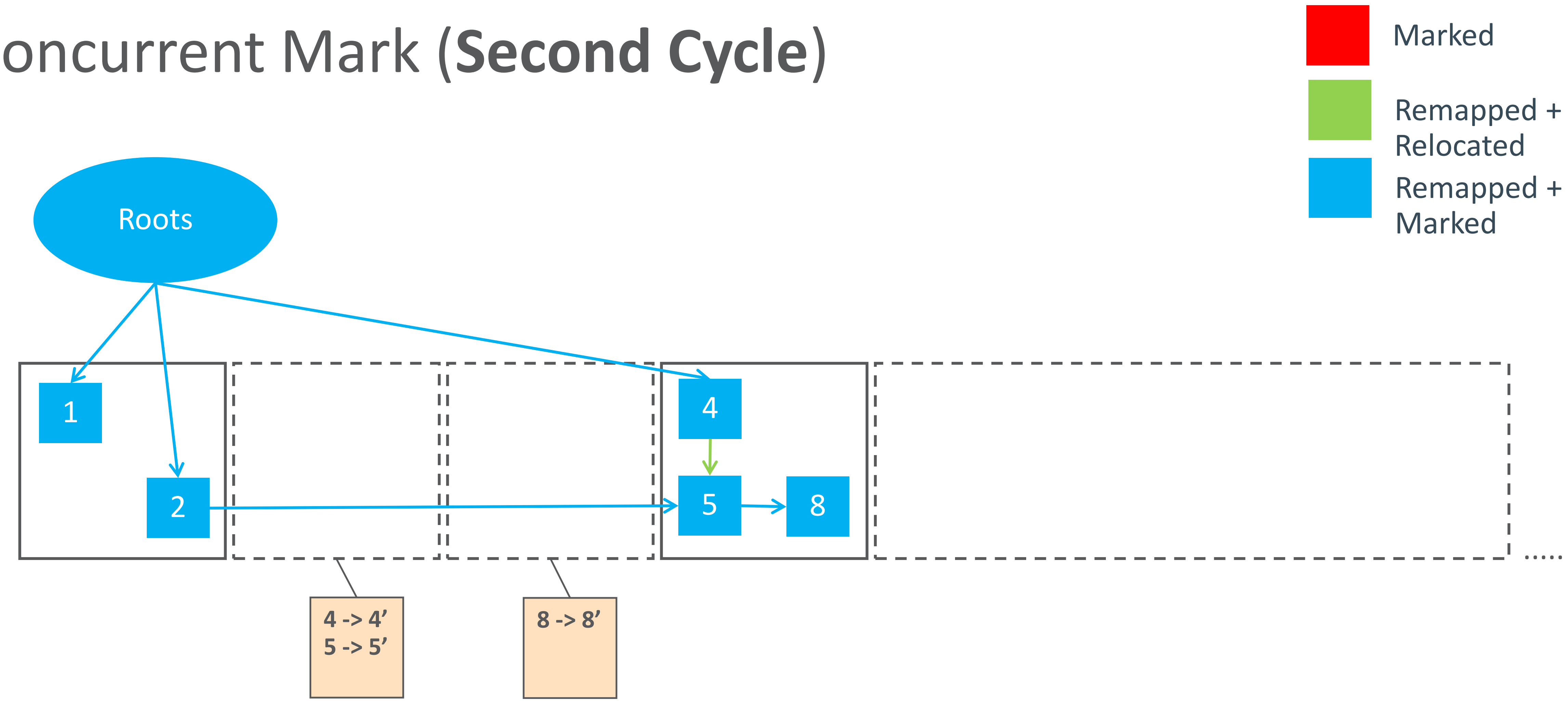
Marked

Remapped + Relocated

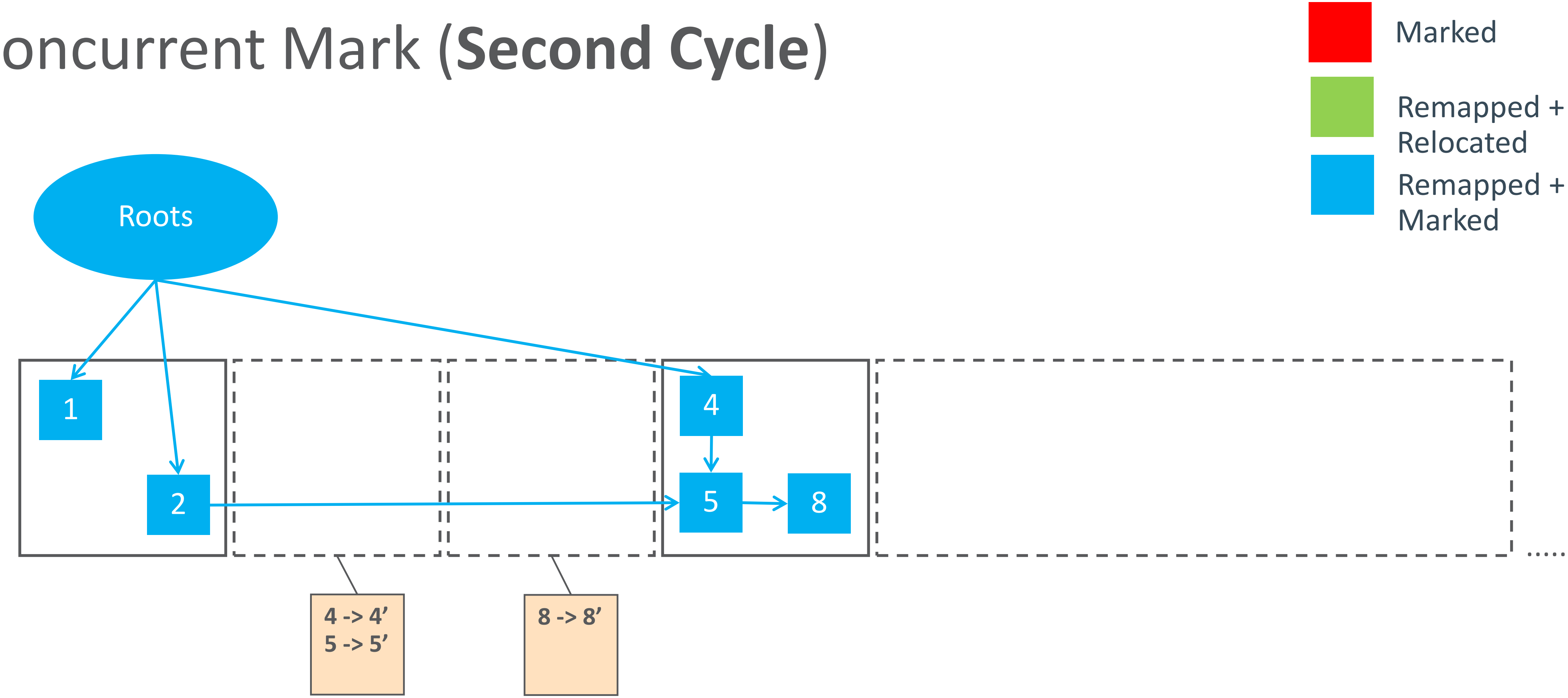
Remapped + Marked



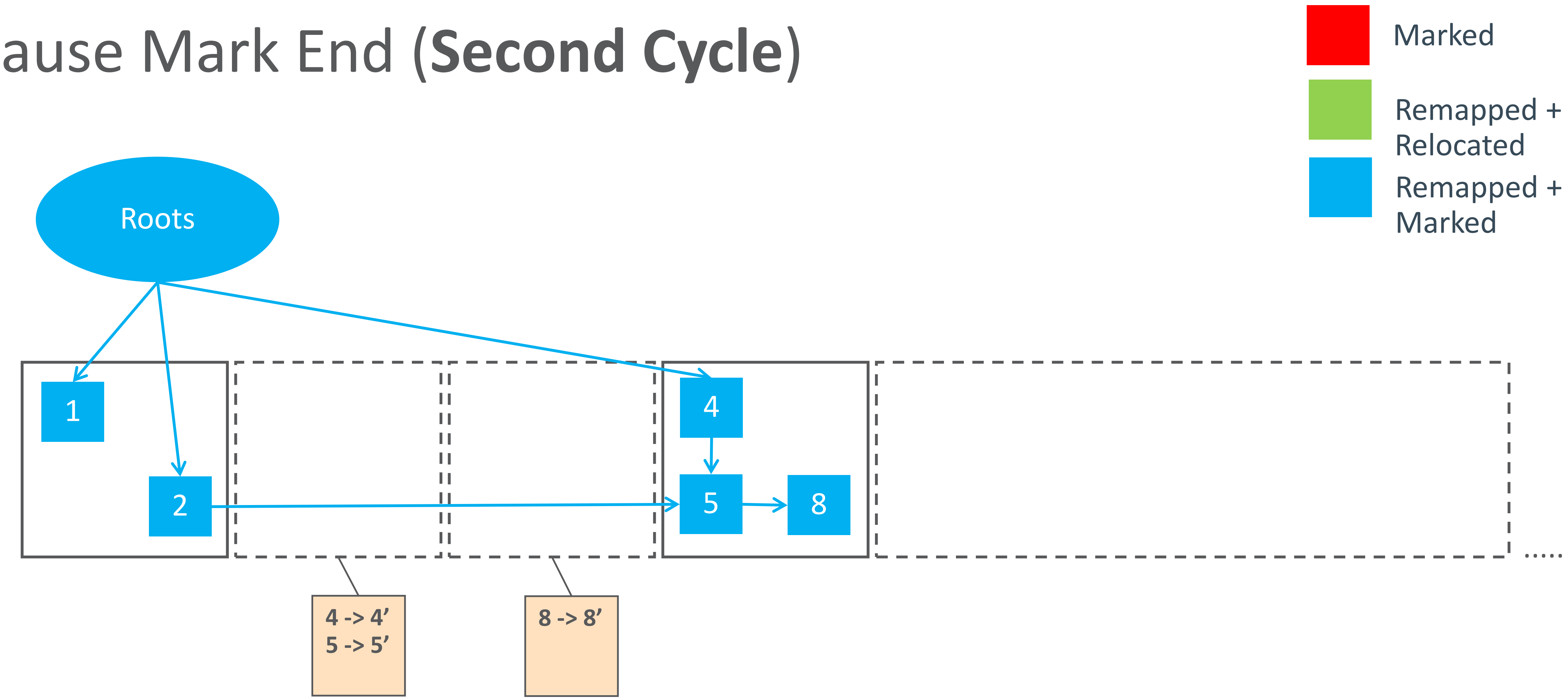
Concurrent Mark (**Second Cycle**)



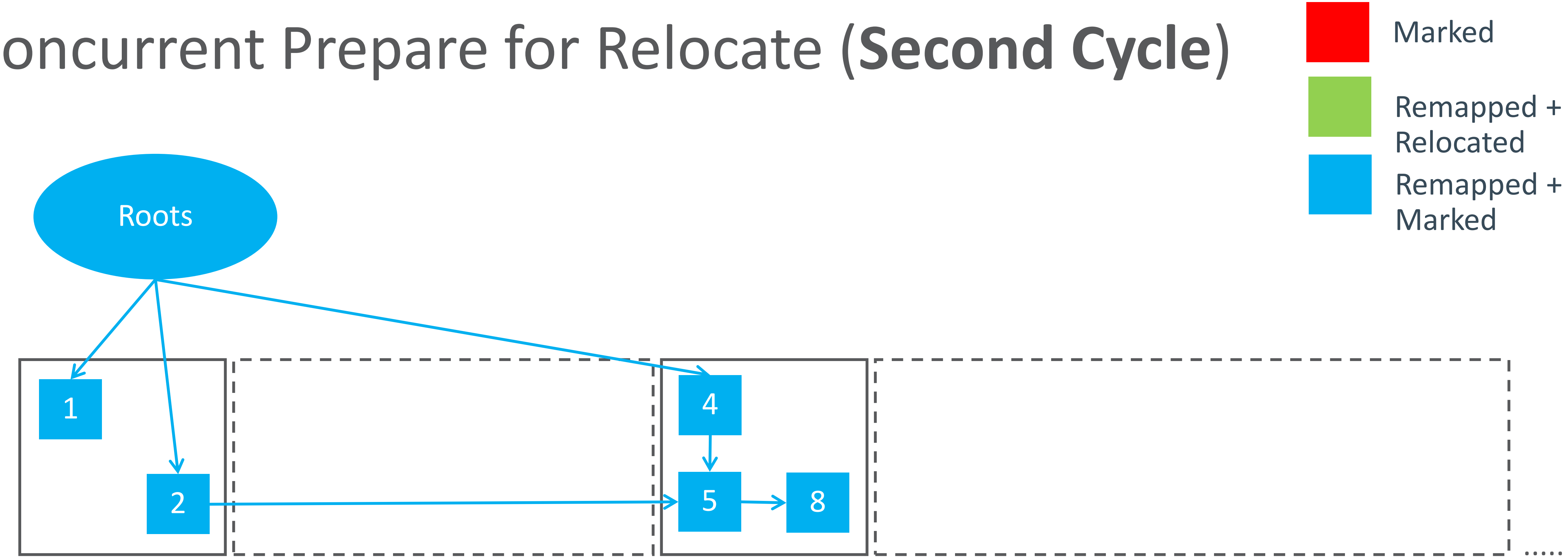
Concurrent Mark (**Second Cycle**)



Pause Mark End (**Second Cycle**)



Concurrent Prepare for Relocate (**Second Cycle**)



Forwarding Tables Freed

Agenda

In The Works

- GC Barrier API
  - Make it **easier** to plug in new GCs (ZGC, Shenandoah, Epsilon)

- Concurrent class unloading & weak roots
  - Traditionally done in a Stop-The-World pause
  - Impacts **JITs** and **Runtime** subsystems

- Addressing non-GC induced latencies
  - Time to safepoint/unsafepoint, object monitor deflation, etc.

Foundation for Future GC Features

Colored Pointers + Load Barriers

- Thread local GC scheme
- Track heap access patterns
- Use non-volatile memory for rarely used parts of the heap
- Compress or archive parts of the heap
- Object properties encoded in pointers
- Allocation tricks
- etc.

Agenda

How To Get Started

Download

- Official **early access builds** will be available soon-ish, but until then…
- Download & build

```
$ hg clone http://hg.openjdk.java.net/zgc/zgc
$ cd zgc
$ sh configure
$ make images
```

- Run

```
$ ./build/linux-x86_64-<...>/images/jdk/bin/java
```

How To Get Started

JVM Options

- Enable ZGC: **-XX:+UseZGC**
- Tuning
  - If you care about latency, do **not** overprovision your machine
  - Max heap size: **-Xmx<size>**
  - Number of concurrent GC threads: **-XX:ConcGCThreads=<number>**
- Logging
  - Basic logging: **-Xlog:gc**
  - Detailed logging useful when tuning: **-Xlog:gc***

Feedback Welcome!

http://wiki.openjdk.java.net/display/zgc/

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