Understanding Low Latency JVM GCs

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Understanding JVM GC: Advanced!

- Concurrent Marking
- Shenandoah
- Azul’s C4
- ZGC
- How to choose a GC algorithm?

Concurrent Marking

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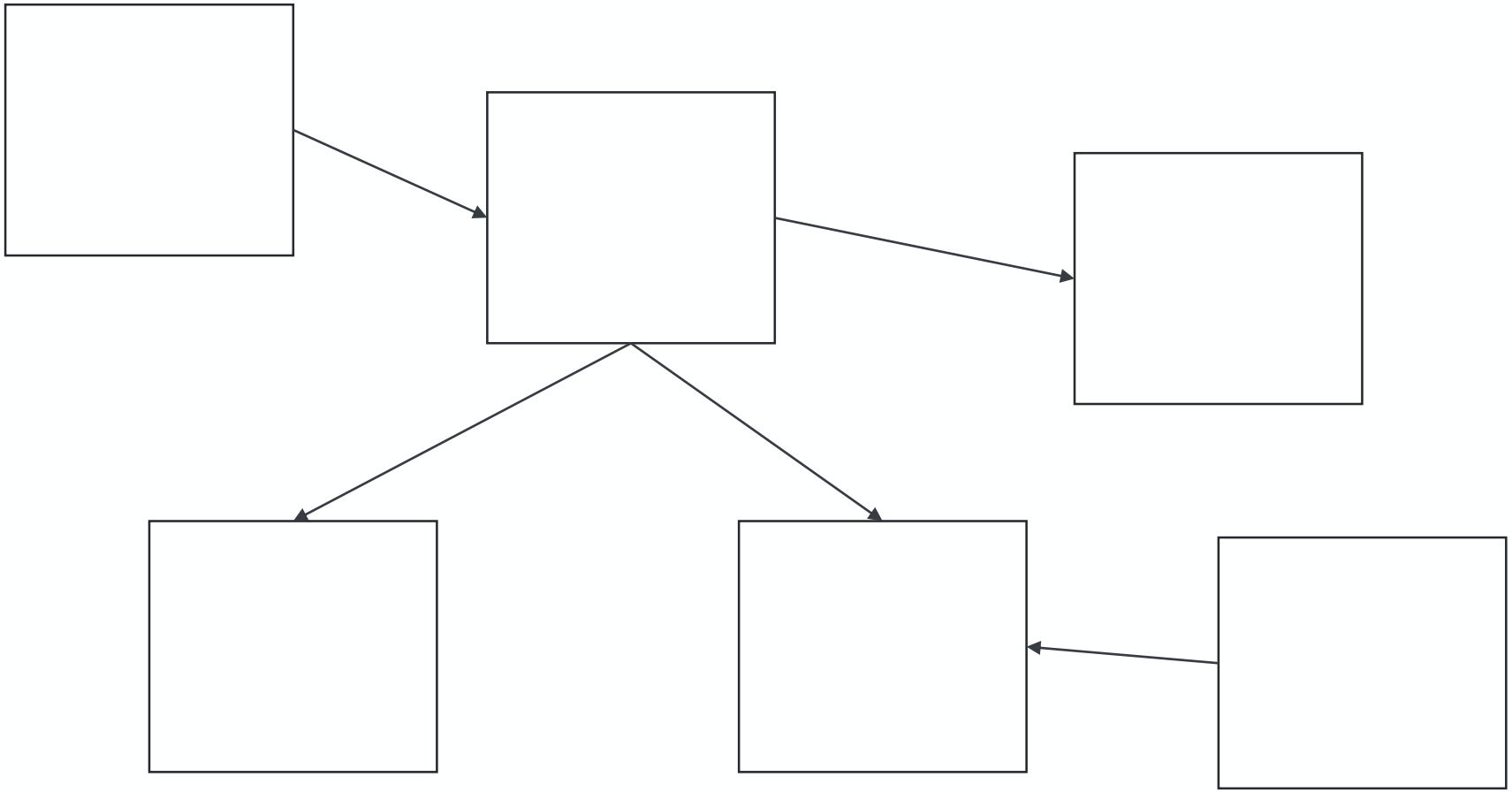
Concurrent Marking

- Used in CMS & G1 algorithms already and by all low latency GCs
- Try to mark the whole object graph concurrently with the application running
- Based on Tri-color abstraction & Snapshot-At-The-Beginning algorithm
  - Used by CMS, G1, Shenandoah

Concurrent Marking: Tri-Color Abstraction



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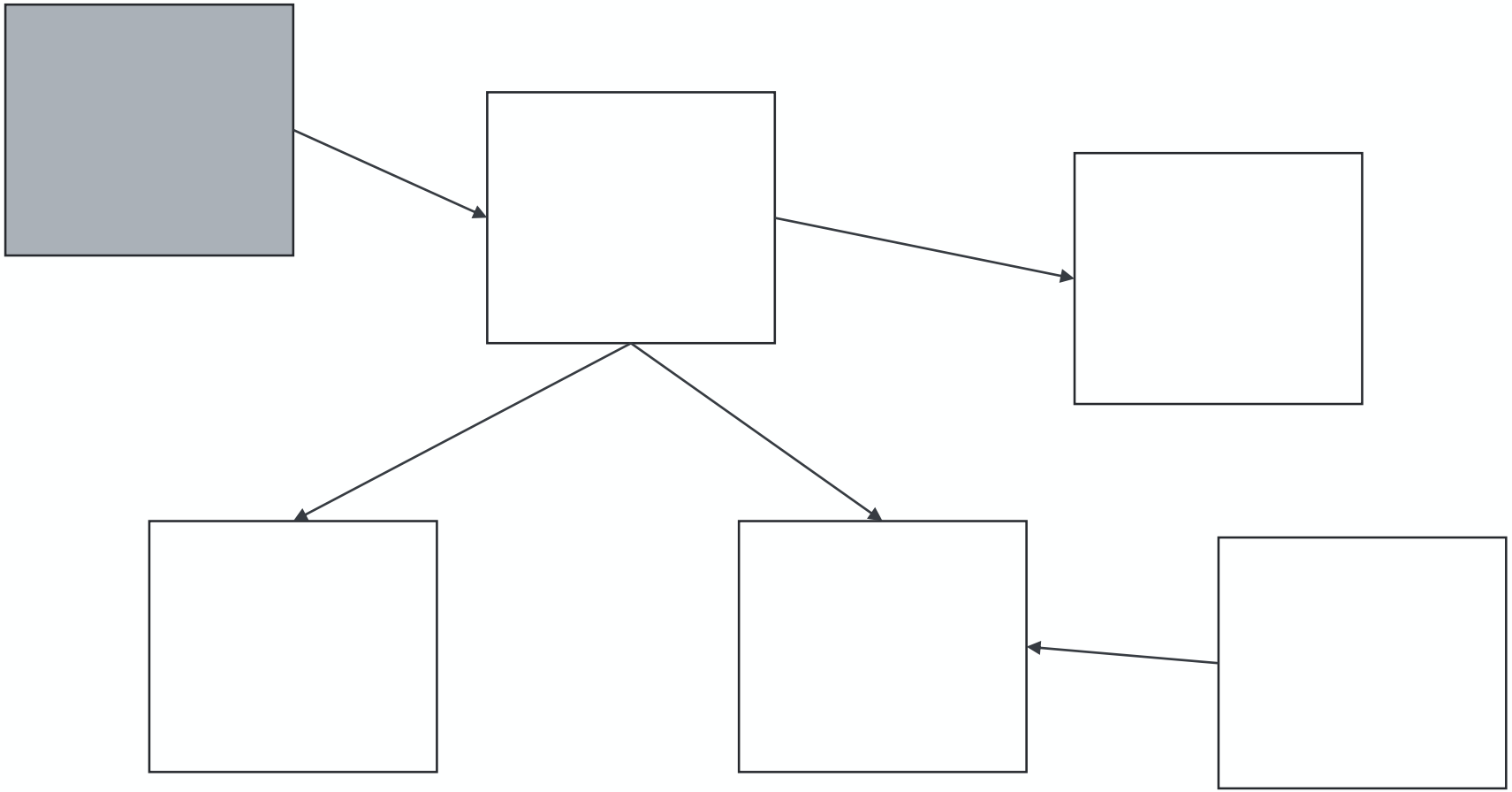

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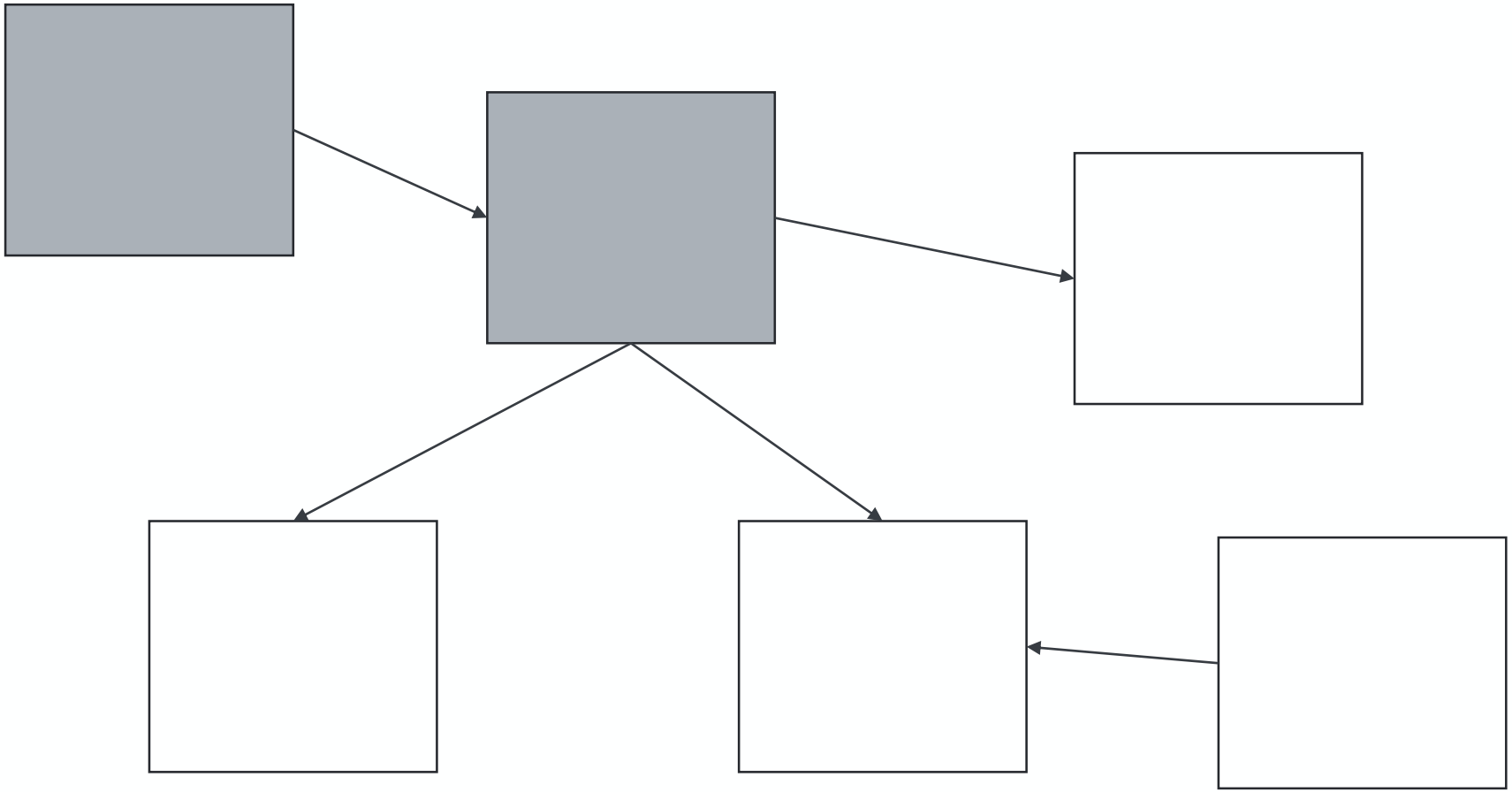

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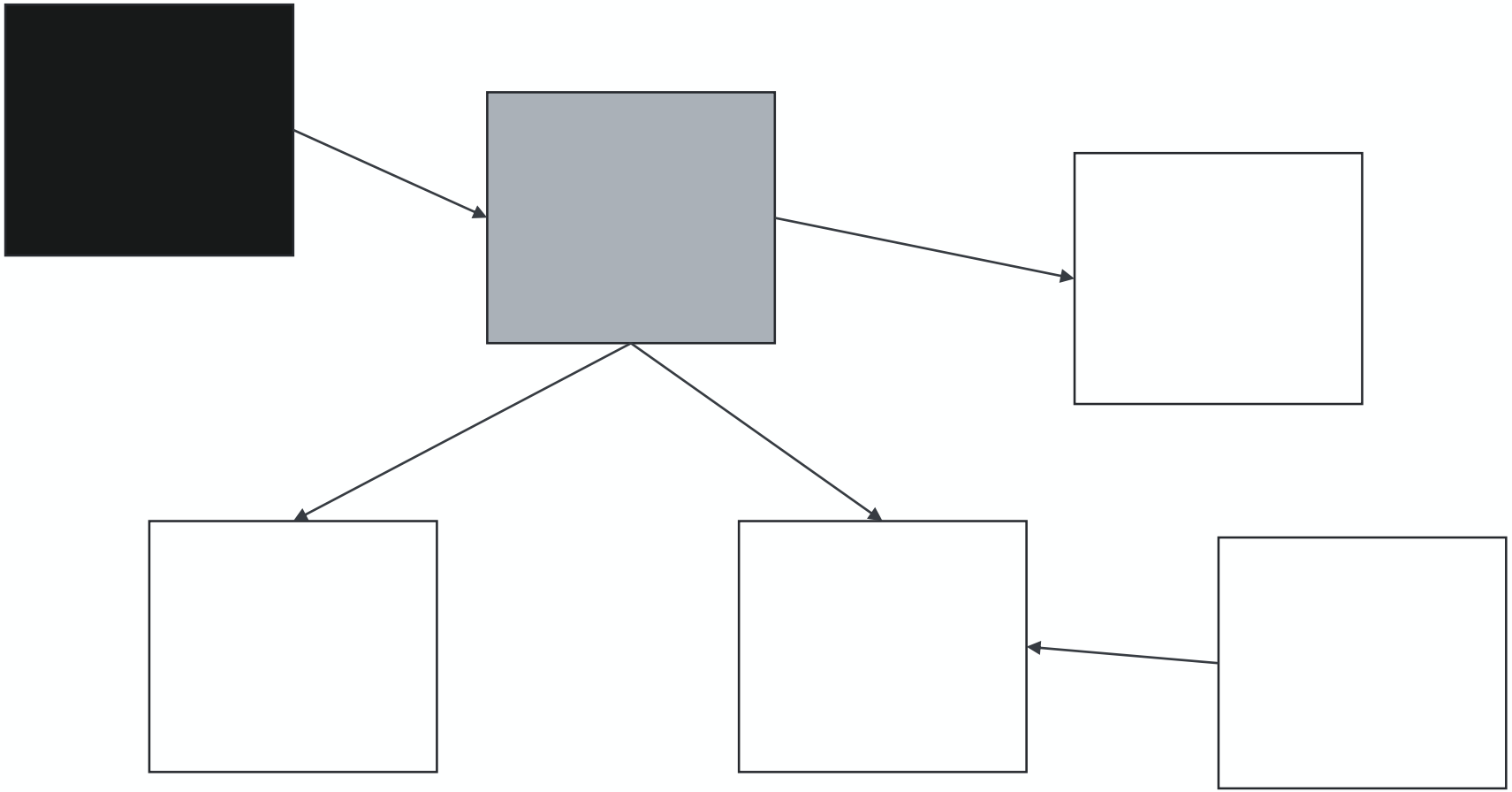

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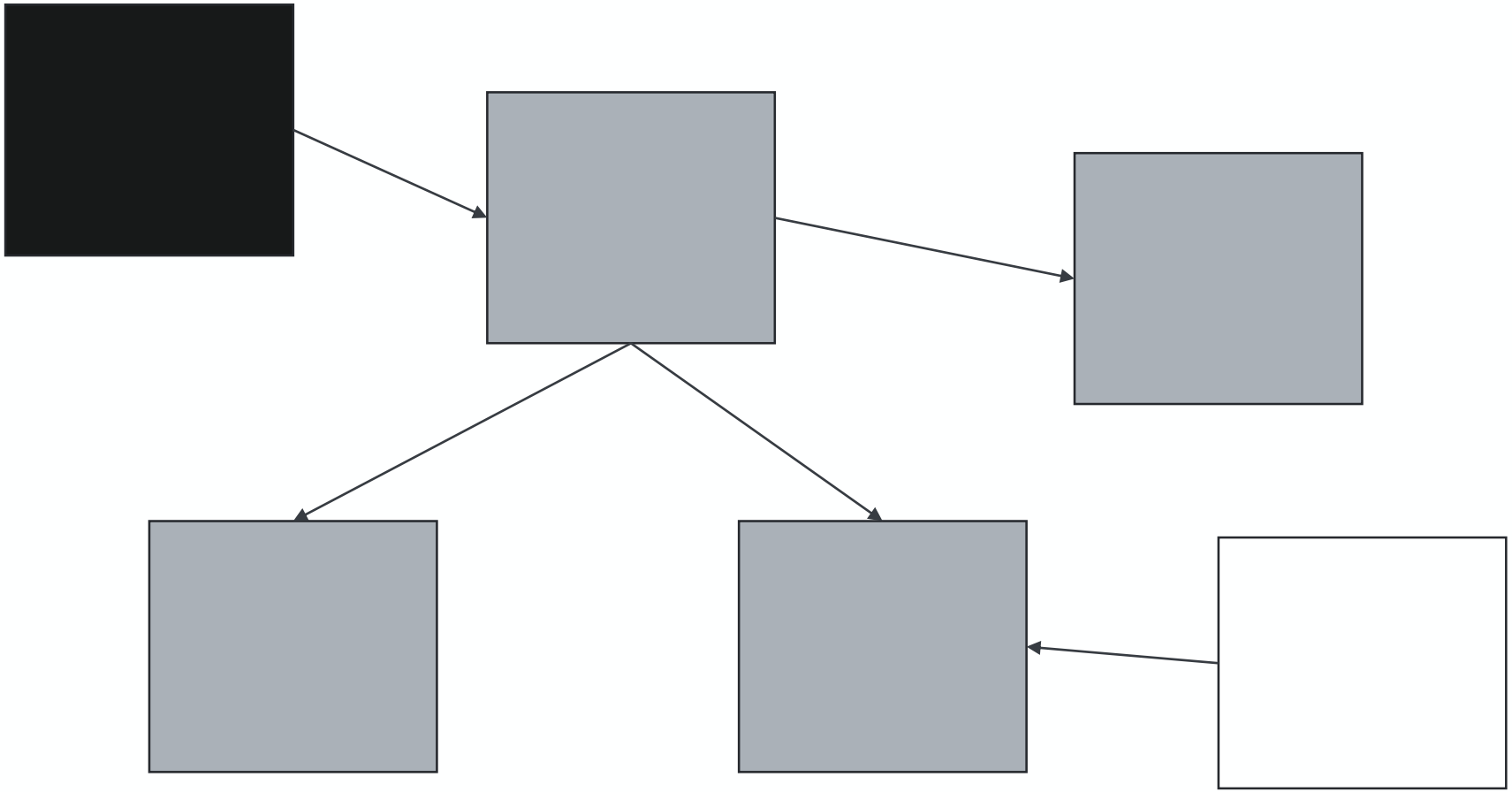

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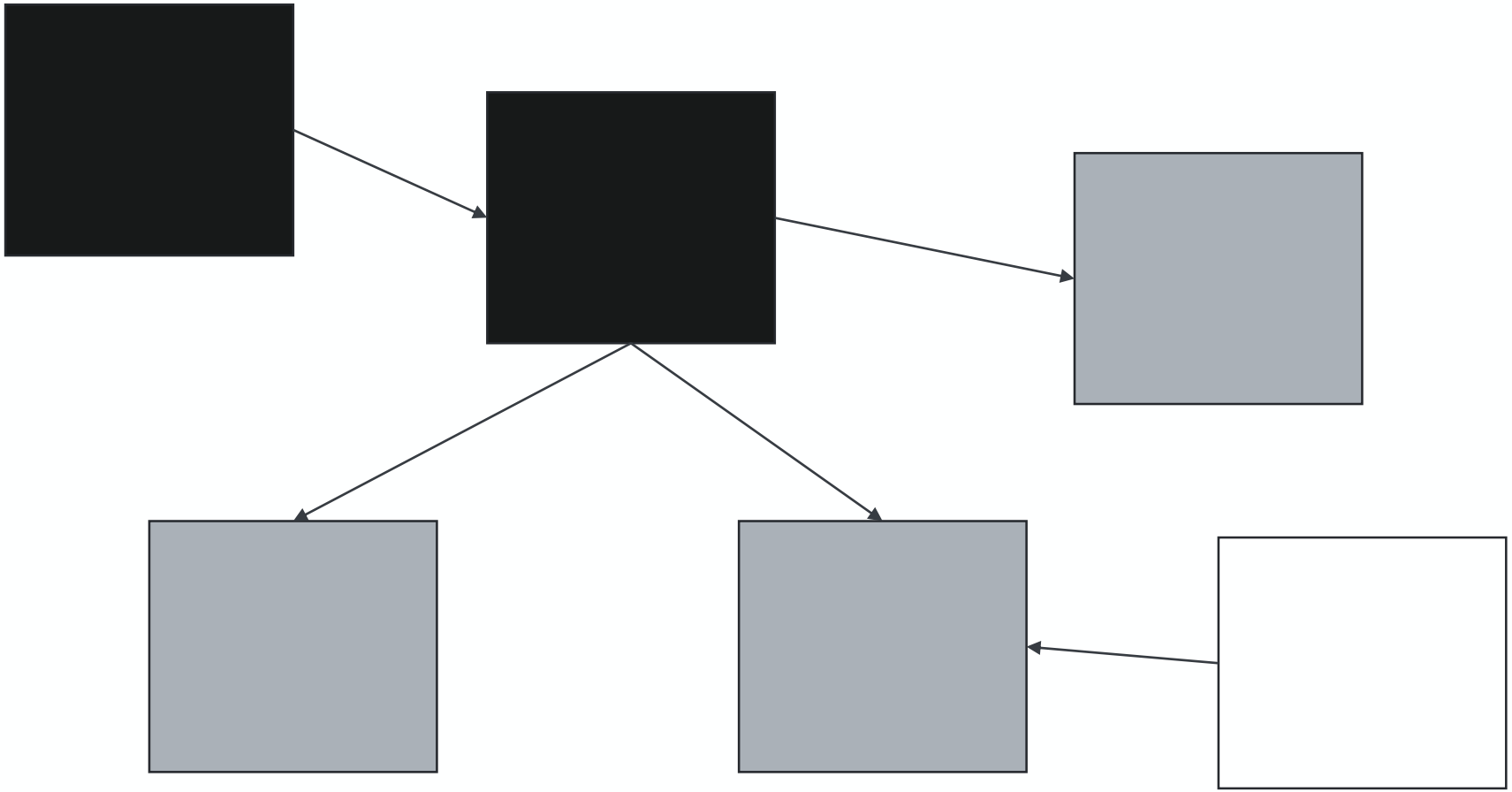

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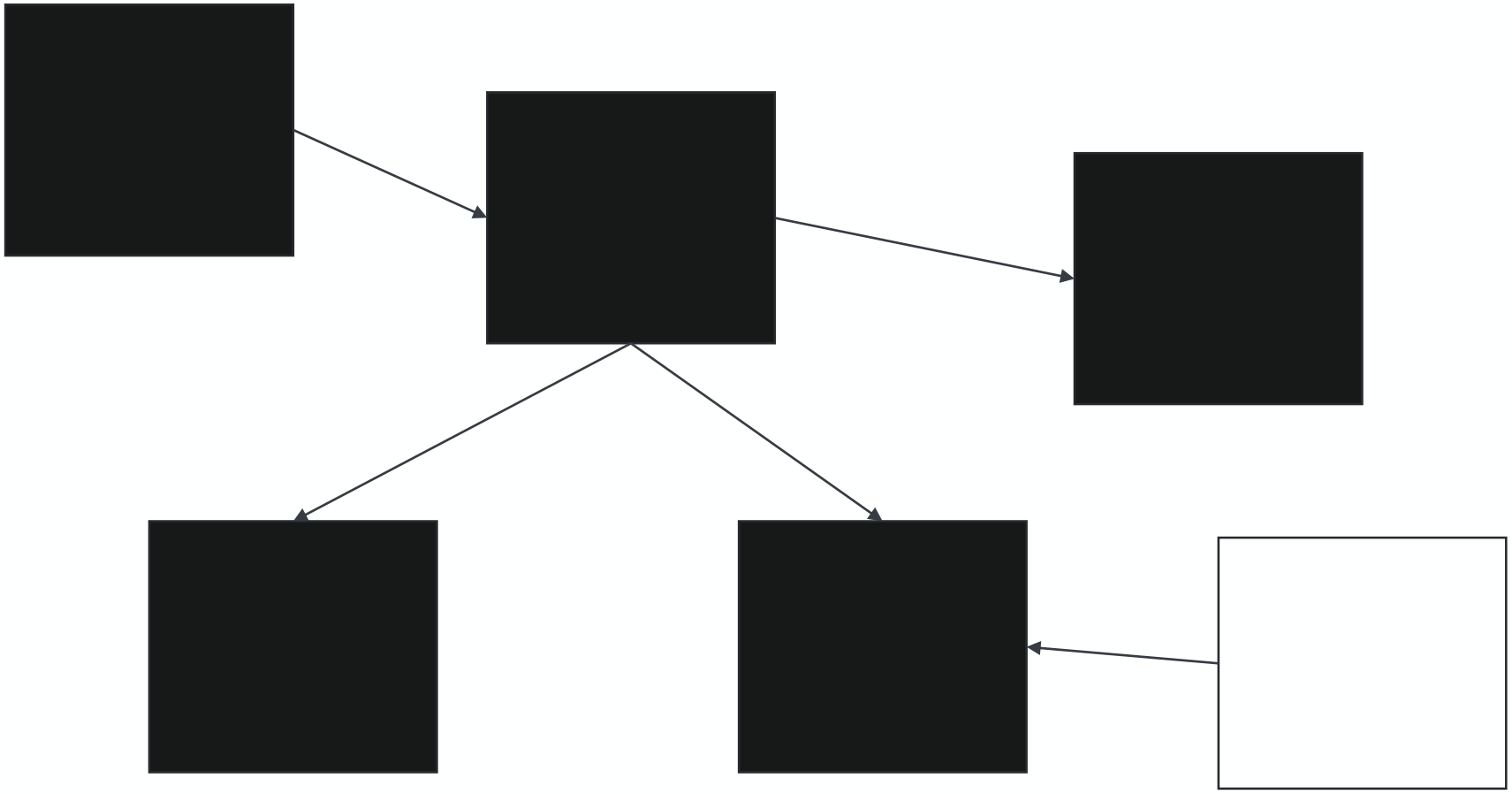

Concurrent Marking: Issues

- New allocations during marking phase can be handled by:
  - Marking automatically object at allocation
  - Not considering new allocations for the current cycle

- Tri-Color abstraction provides 2 properties of missed object:

  1. The mutator stores a reference to a white object into a black object.
  2. All paths from any gray objects to that white object are destroyed.

http://www.memorymanagement.org/glossary/s.html#term-snapshot-at-the-beginning

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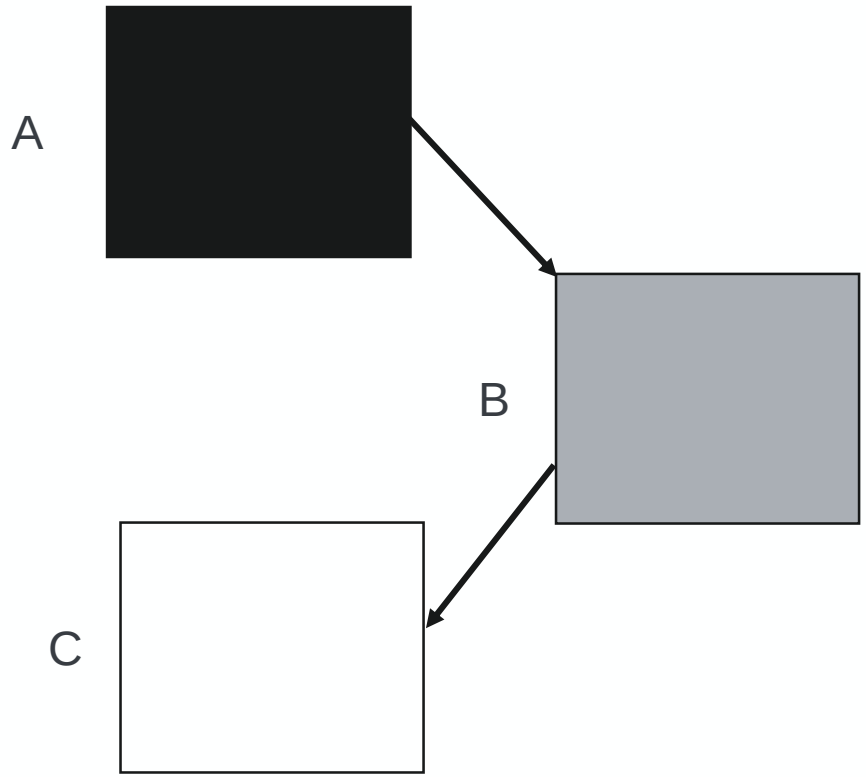
Concurrent Marking: Issues




```
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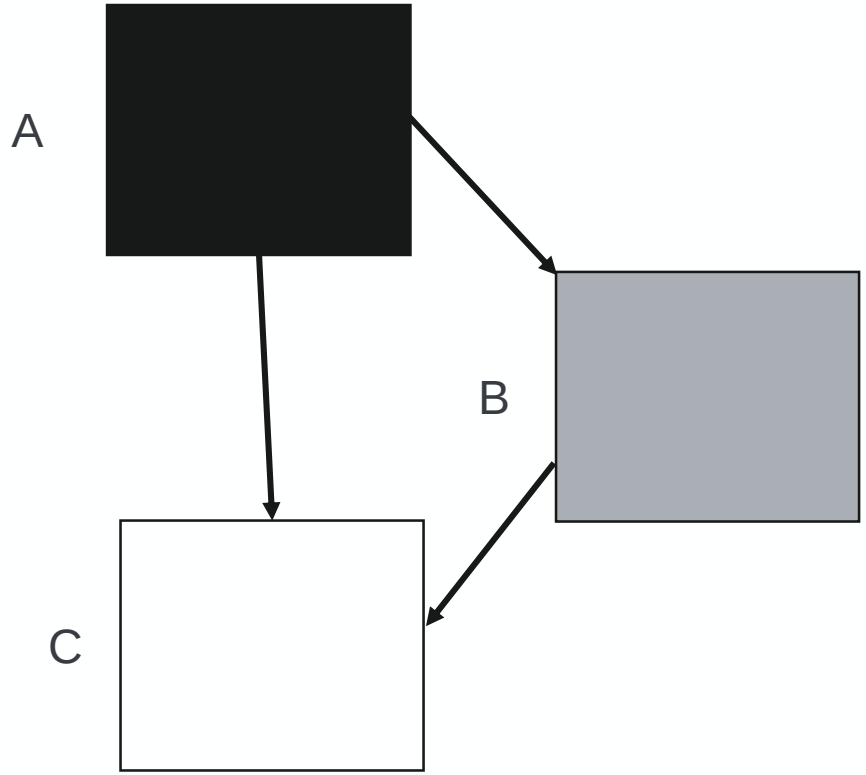


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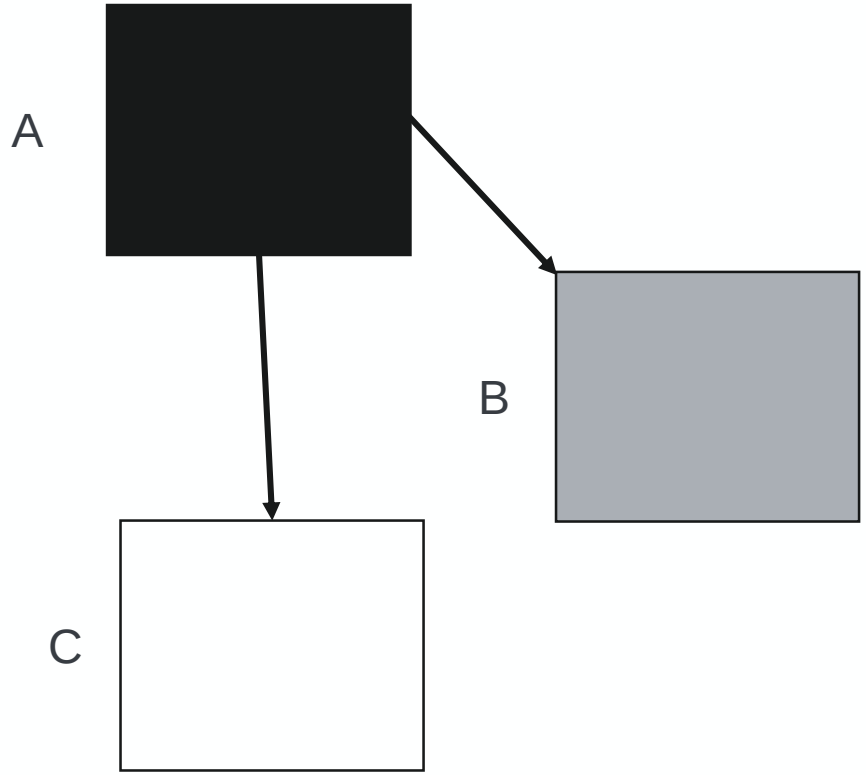


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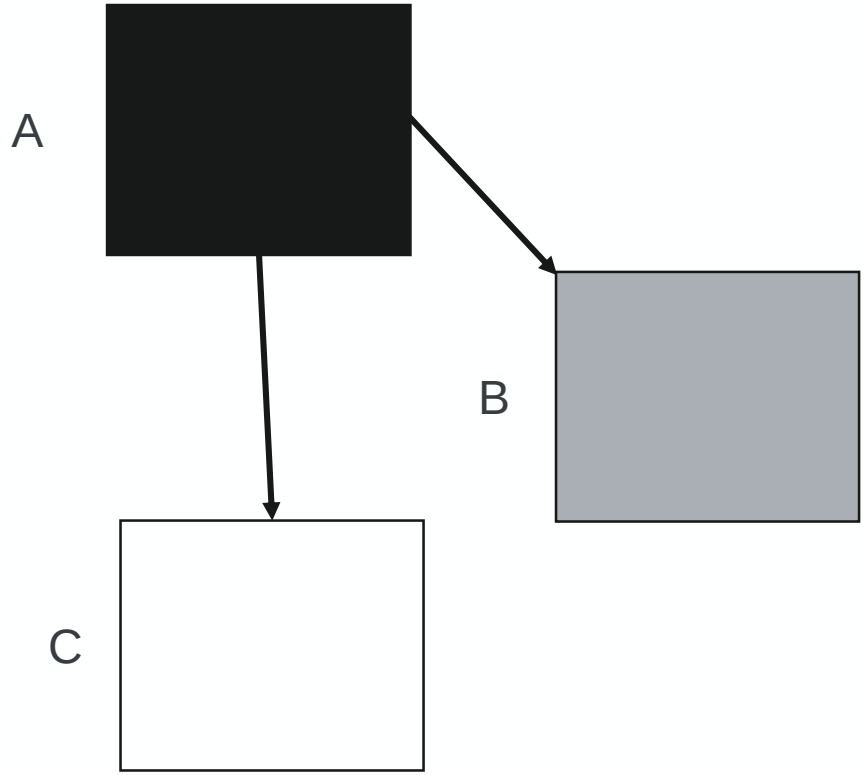


```
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```

OOPS!

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Concurrent Marking: Resolving misses

- 2 ways to ensure not missing any marking
  - Snapshot-At-The-Beginning
  - Incremental Update

- For SATB, Pre-Write Barriers, recording object for marking
  - Before a reference assignation (`X.f = Y`)

- SATB barrier is only active when Marking is on (global state)

```
if (SATB_WriteBarrier) {
  if (X.f != null)
     SATB_enqueue(X.f);
}
```

```
cmp     BYTE PTR [r15+0x30],0x0
jne     0x000002965edc62e5
[...]
mov     r11d,DWORD PTR [rbp+0x74]
test    r11d,r11d
je      0x000002965edc6253
mov     r10,QWORD PTR [r15+0x38]
mov     rcx,r11
shl     rcx,0x3
test    r10,r10
je      0x000002965edc6318
mov     r11,QWORD PTR [r15+0x48]
mov     QWORD PTR [r11+r10*1-0x8],rcx
add     r10,0xfffffffffffffff8
mov     QWORD PTR [r15+0x38],r10
jmp     0x000002965edc6253
mov     rdx,r15
movabs r10,0x7ffac2febc50
call    r10
jmp     0x000002965edc6253
```


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Shenandoah

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Shenandoah GC

- Non-generational (still option for partial collection)
- Region based
- Use Read Barrier: Brooks pointer
- Self-Healing
  - Cooperation between mutator threads & GC threads
  - Only for concurrent compaction
- Mostly based on G1 but with concurrent compaction

Shenandoah Phases

- Initial Marking (STW)
- Concurrent Marking
- Final Remark (STW)
- Concurrent Cleanup
- Concurrent Evacuation
- Init Update References (STW)
- Concurrent Update References
- Final Update References (STW)
- Concurrent Cleanup

Concurrent Marking

- SATB-style (like G1)
- 2 STW pauses for Initial Mark & Final Remark
- Conditional Write Barrier
  - To deal with concurrent modification of object graph

Concurrent Evacuation

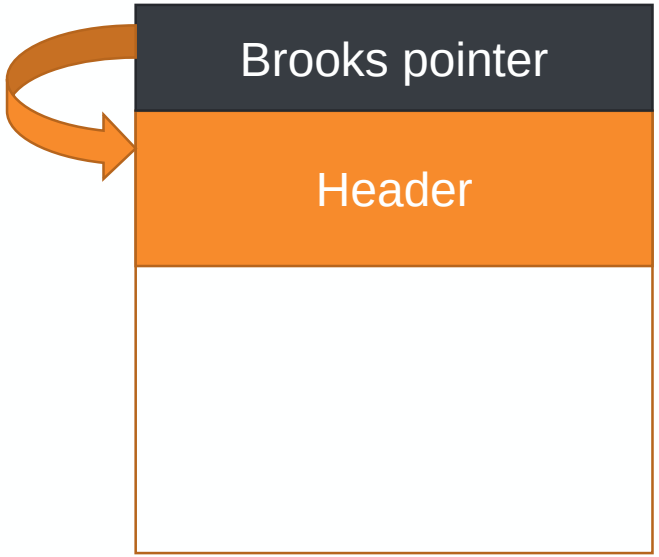
- Same principle than G1:
  - Build CollectionSet with Garbage First!
  - Evacuate to new regions to release the region for reuse

- Concurrent Evacuation done with the help of:
  - 1 Read Barrier : Brooks pointer
  - 4 Write Barriers

- Barriers help to keep the to-space invariant:
  - All Writes are made into an object in to-space

Brooks pointers

- All objects have an additional forwarding pointer
  - Placed before the regular object



- Dereference the forwarding pointer for each access
  - Memory footprint overhead
  - Throughput overhead

```
mov     r13,QWORD PTR [r12+r14*8-0x8]
```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Write Barriers

- Any writes (even primitives) to from-space object needs to be protected

```
if (evacInProgress
  && inCollectionSet(obj)
  && notCopyYet(obj)) {
    evacuateObject(obj)
}
```

```
test   BYTE PTR [r15+0x3c0],0x2
jne    0x00000000281bcbc
[...]
mov    r10d,DWORD PTR [r13+0xc]
test   r10d,r10d
je     0x00000000281bc2b
mov    r11,QWORD PTR [r15+0x360]
mov    rcx,r10
shl    rcx,0x3
test   r11,r11
je     0x00000000281bd0d
[...]
mov    rdx,r15
movabs r10,0x62d1f660
call   r10
jmp    0x00000000281bc2b
```

- Exotic barriers:
  - acmp (pointer comparison)
  - CAS
  - clone

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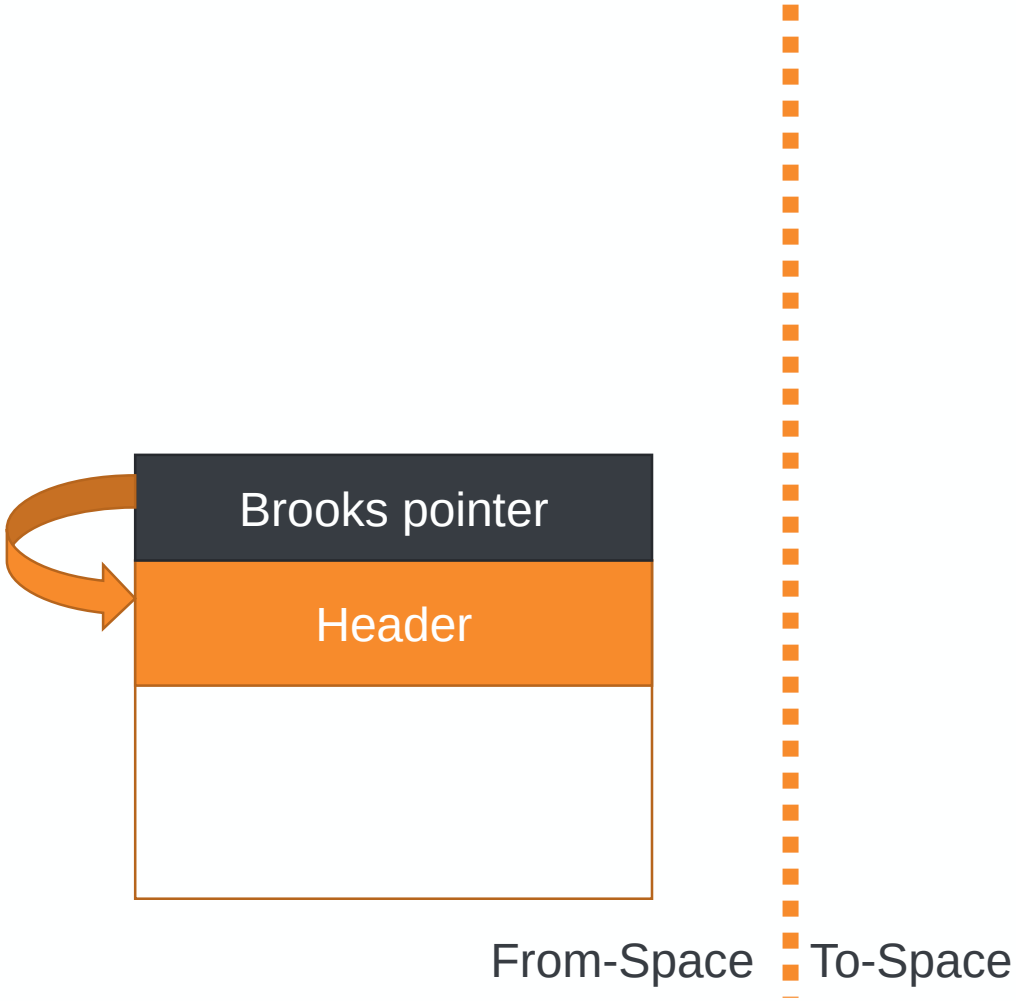
Concurrent Copy: GC thread



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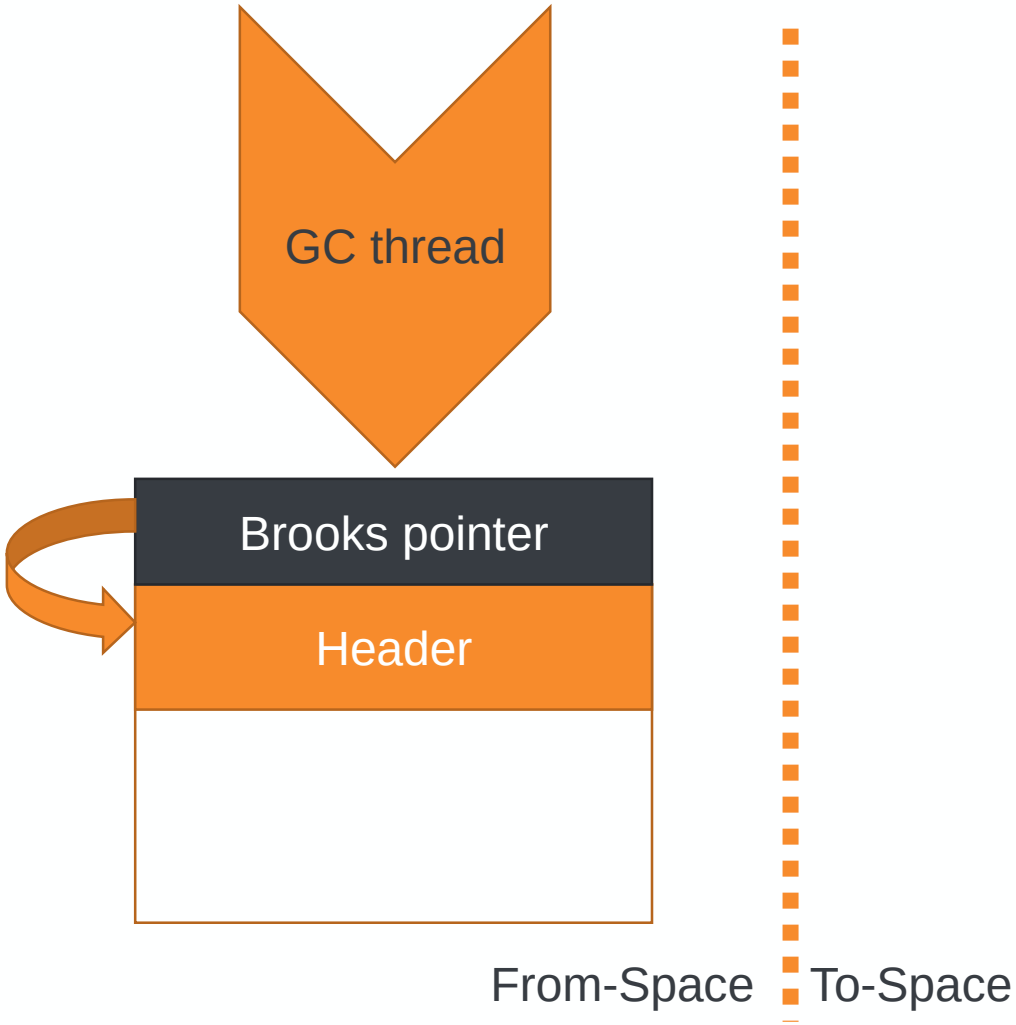

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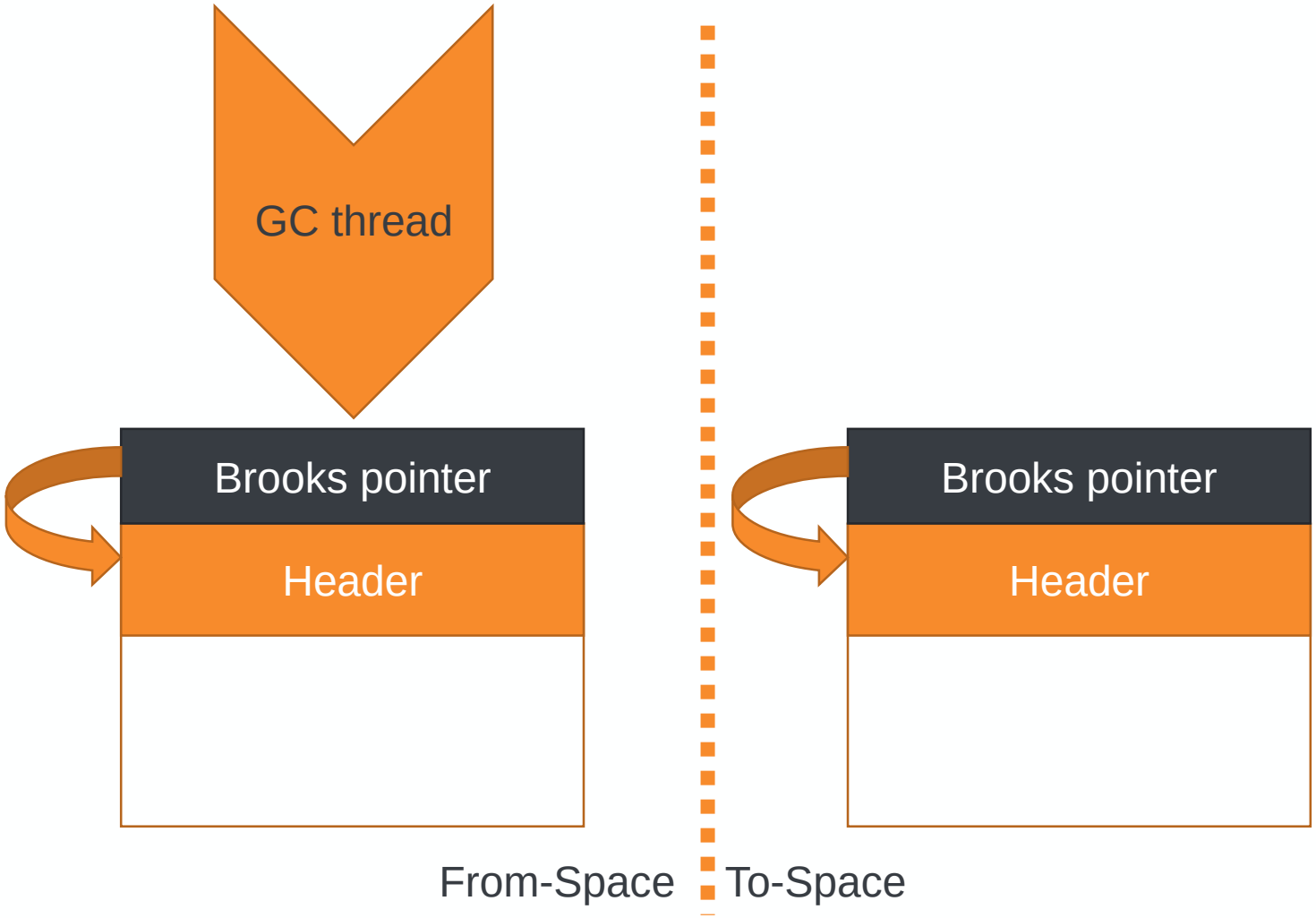

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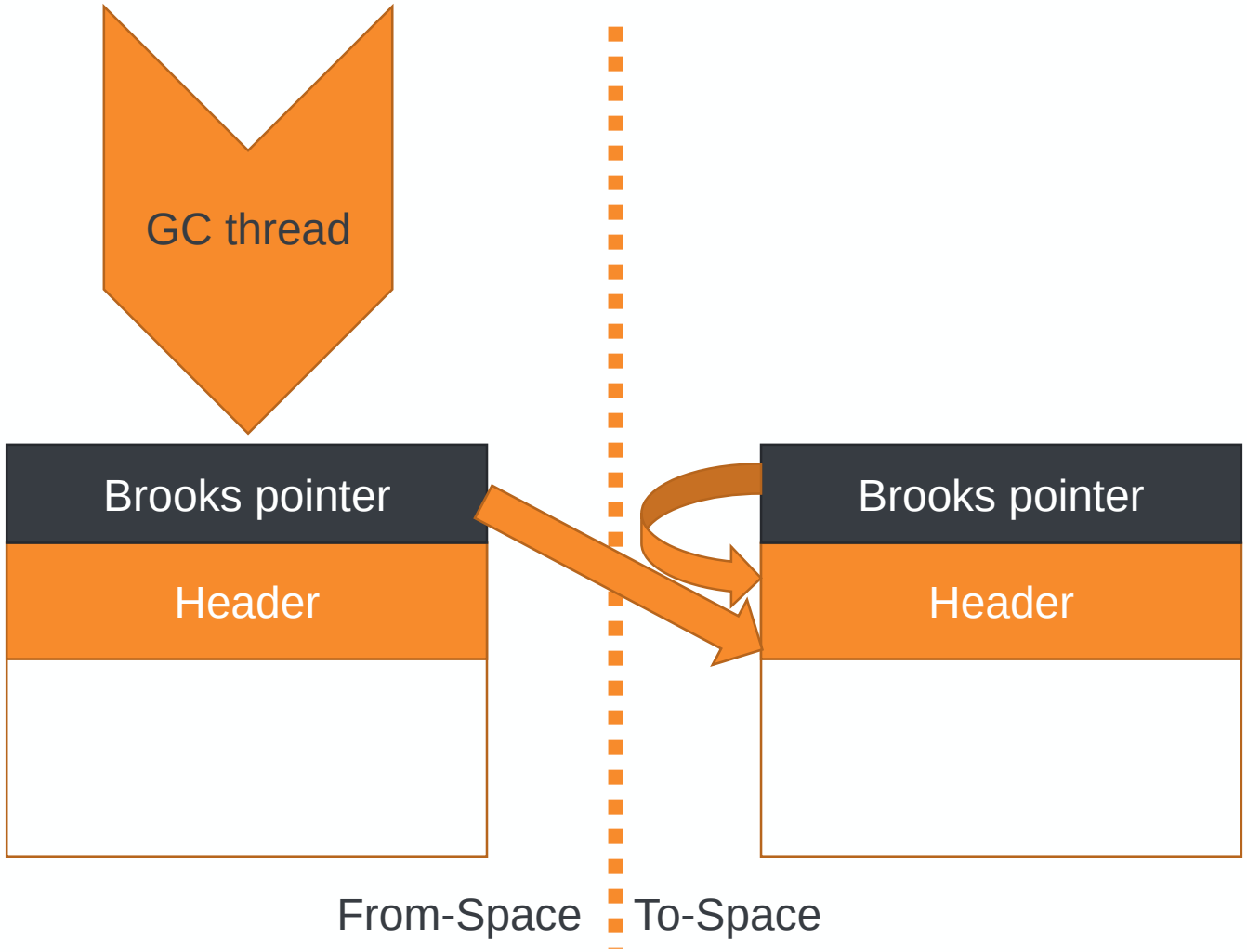

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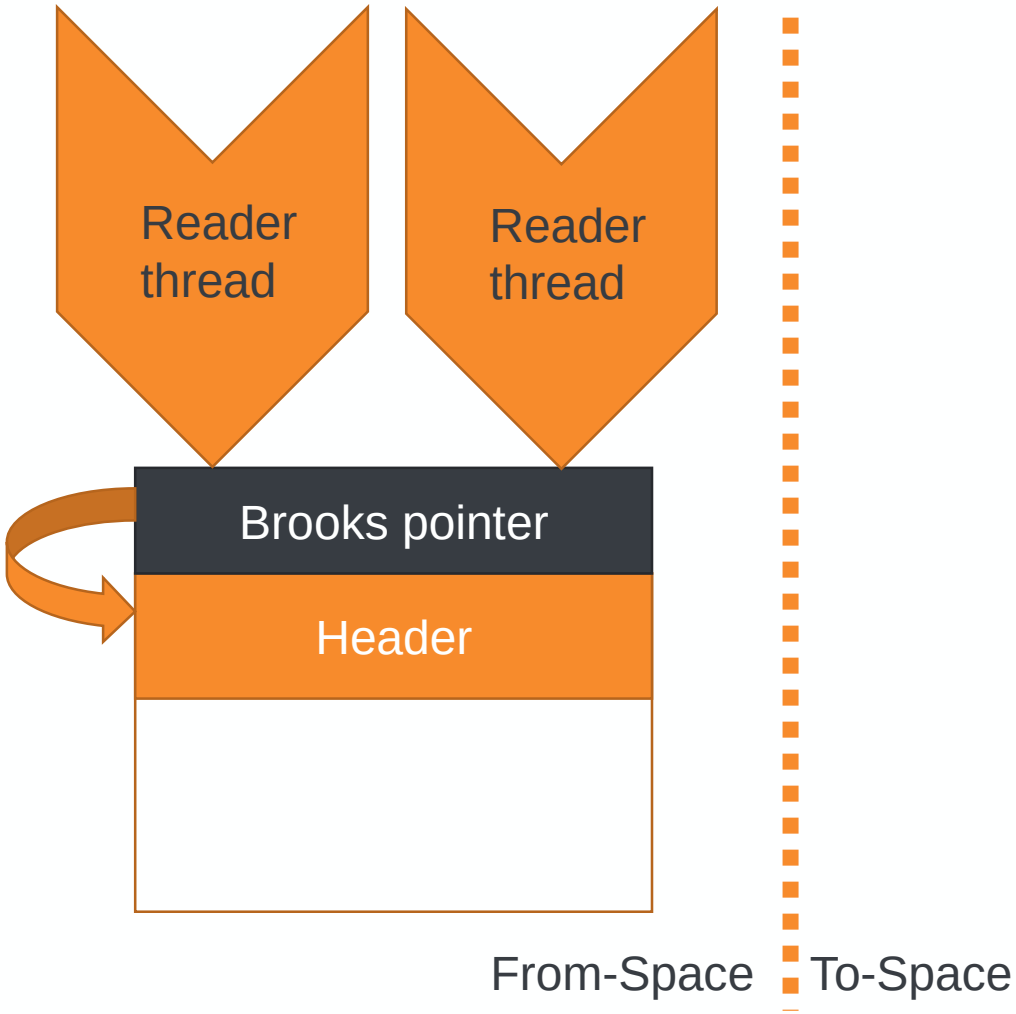
Concurrent Copy: Reader threads



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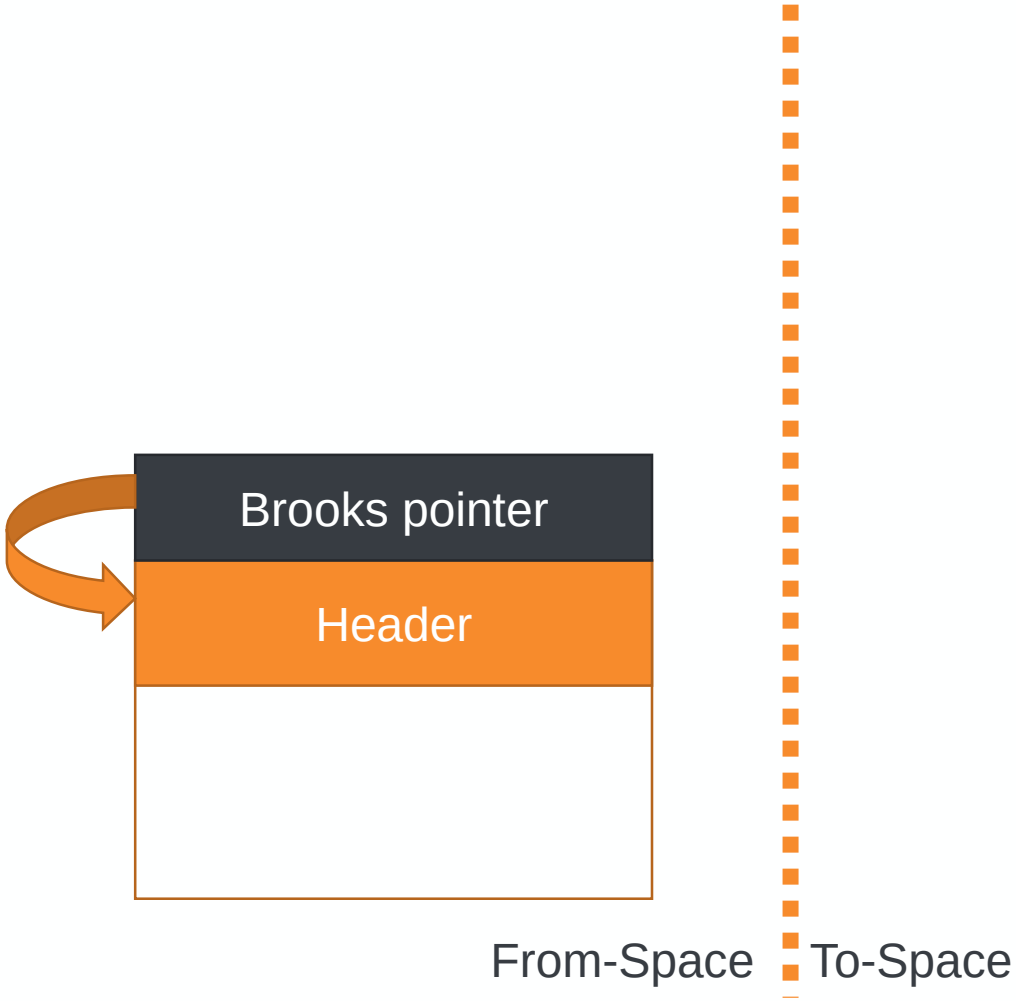
Concurrent Copy: Writer threads



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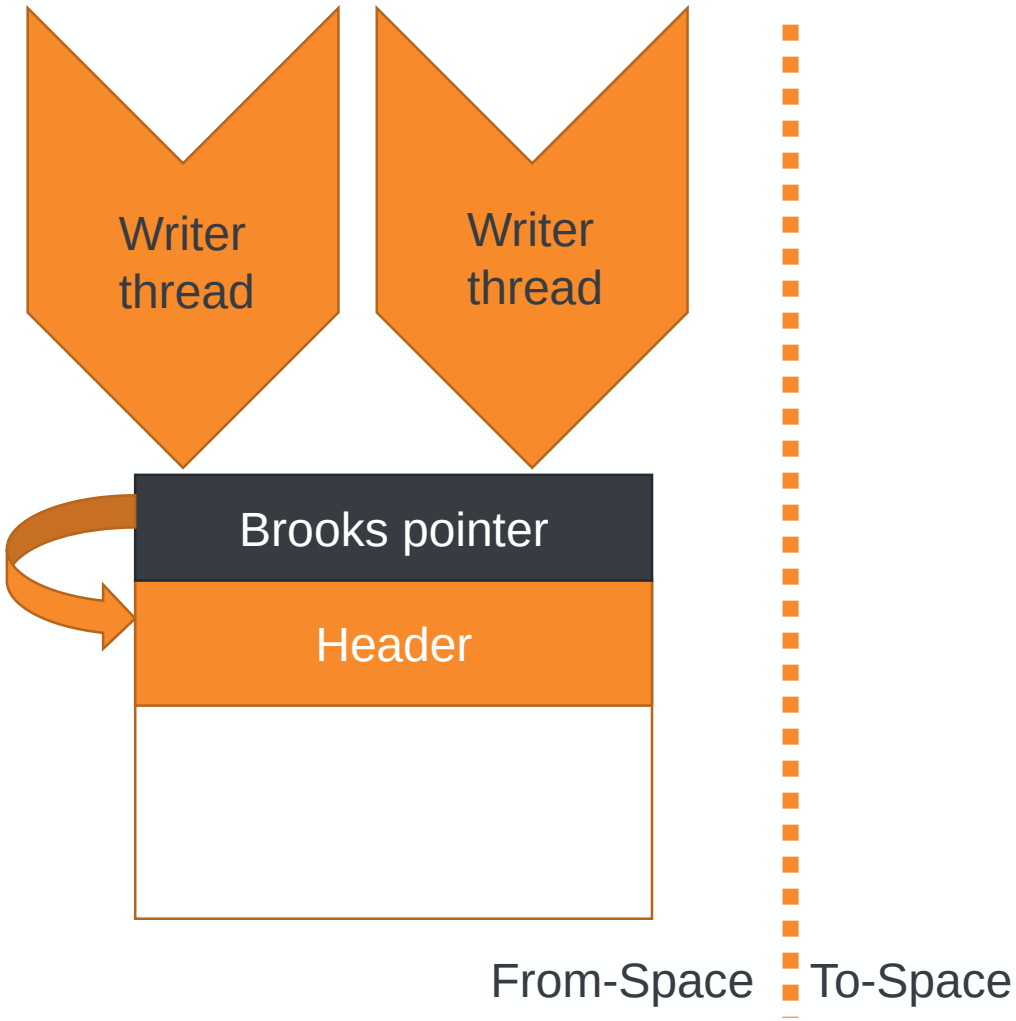

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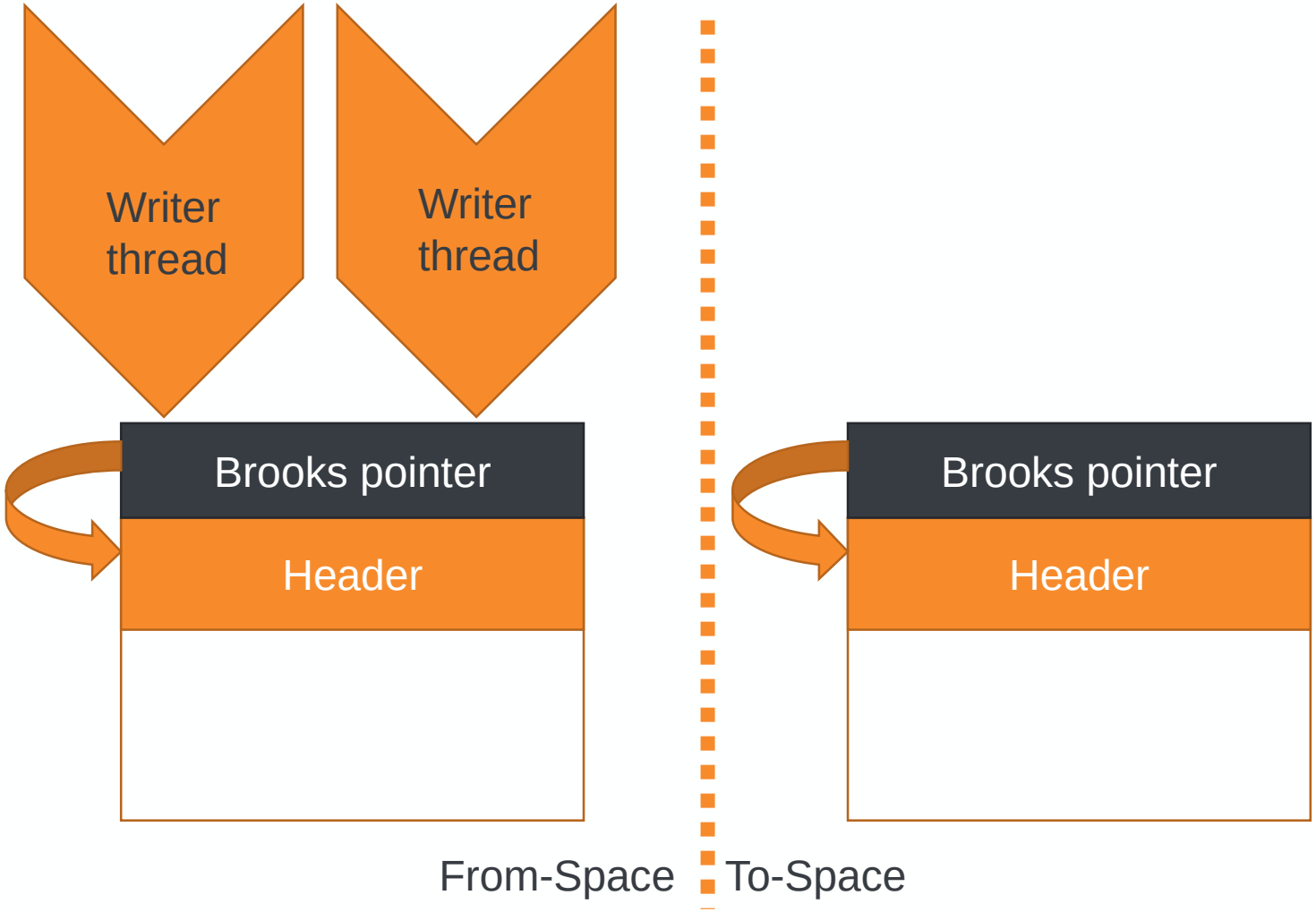

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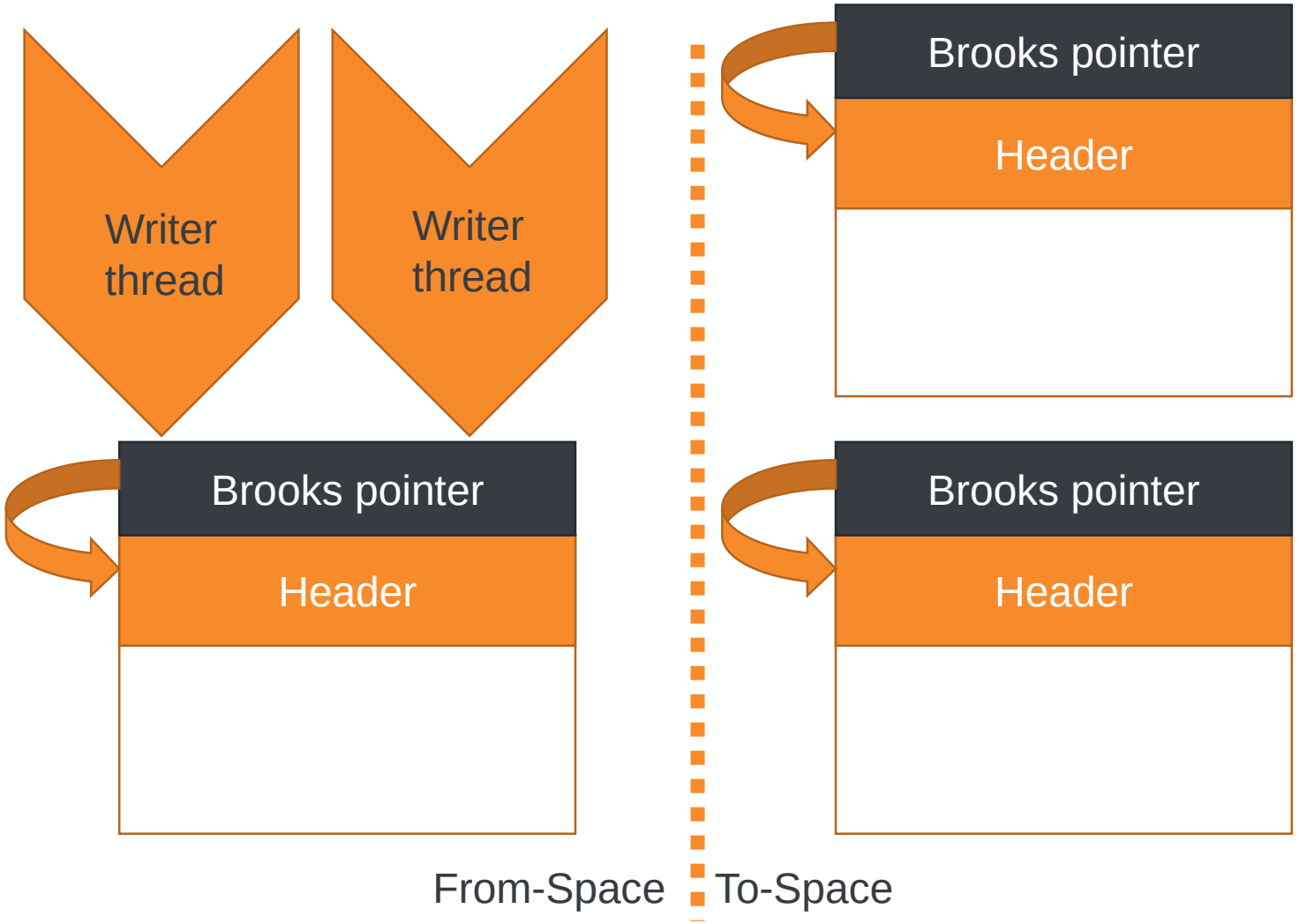

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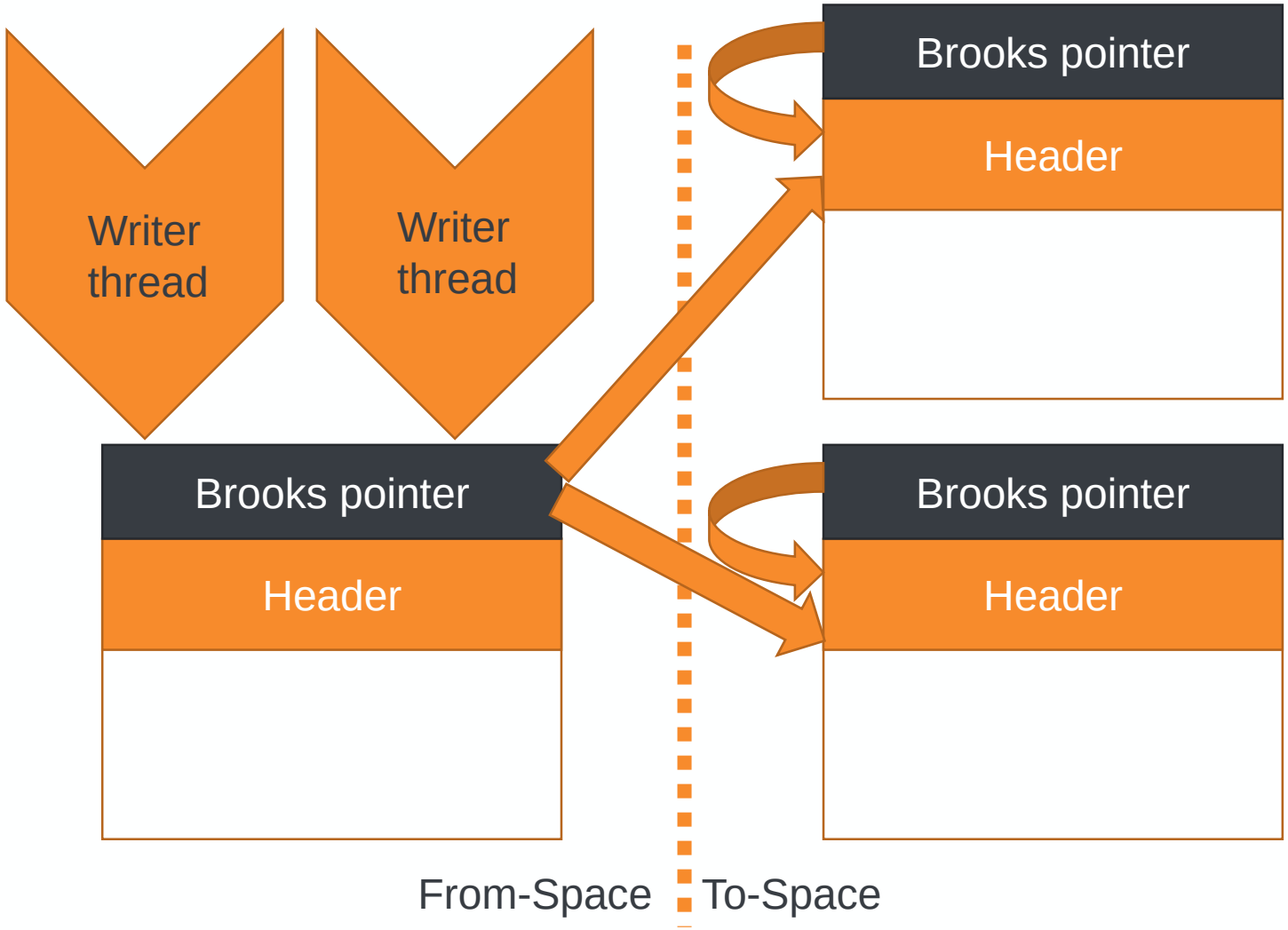

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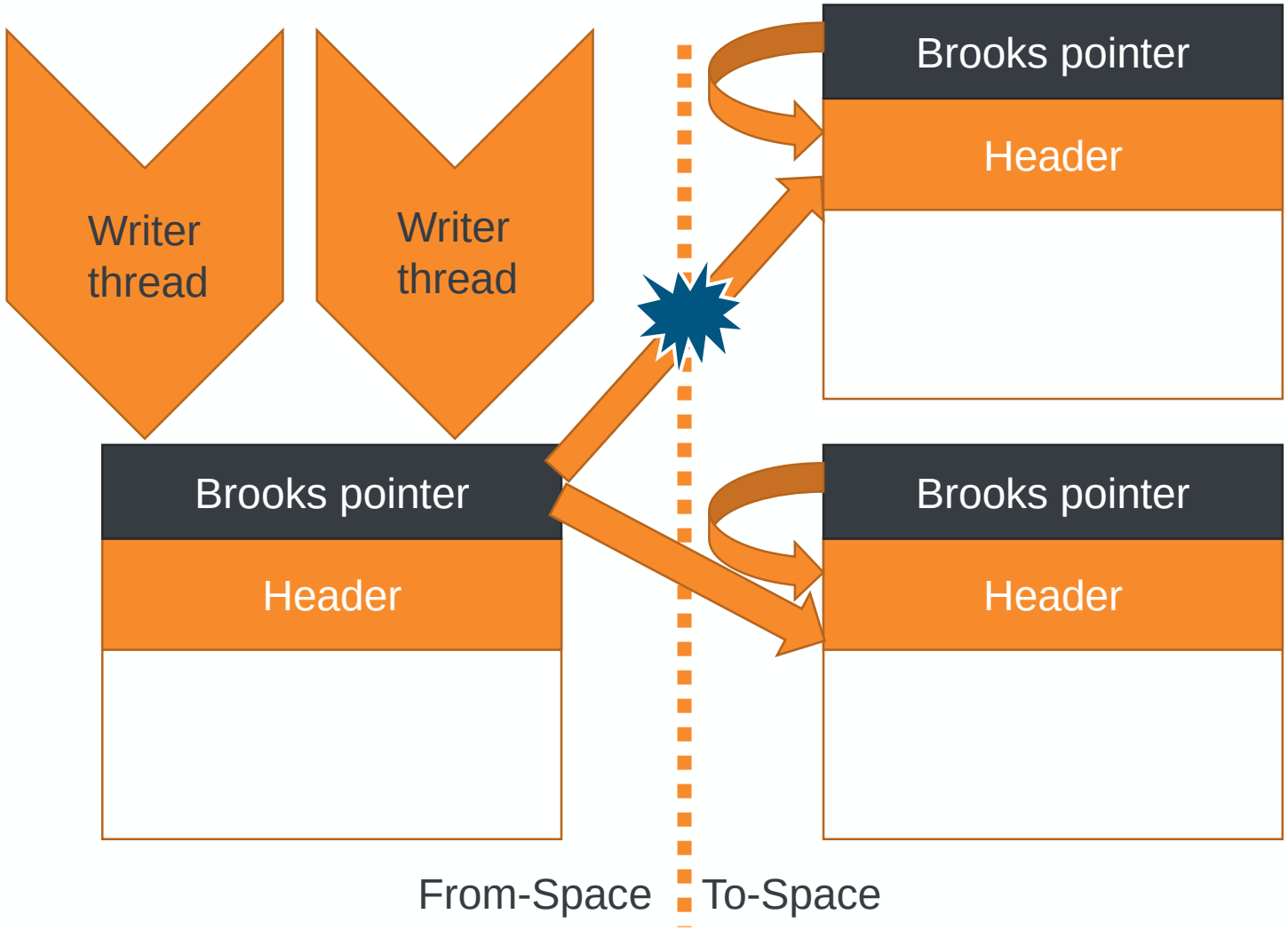

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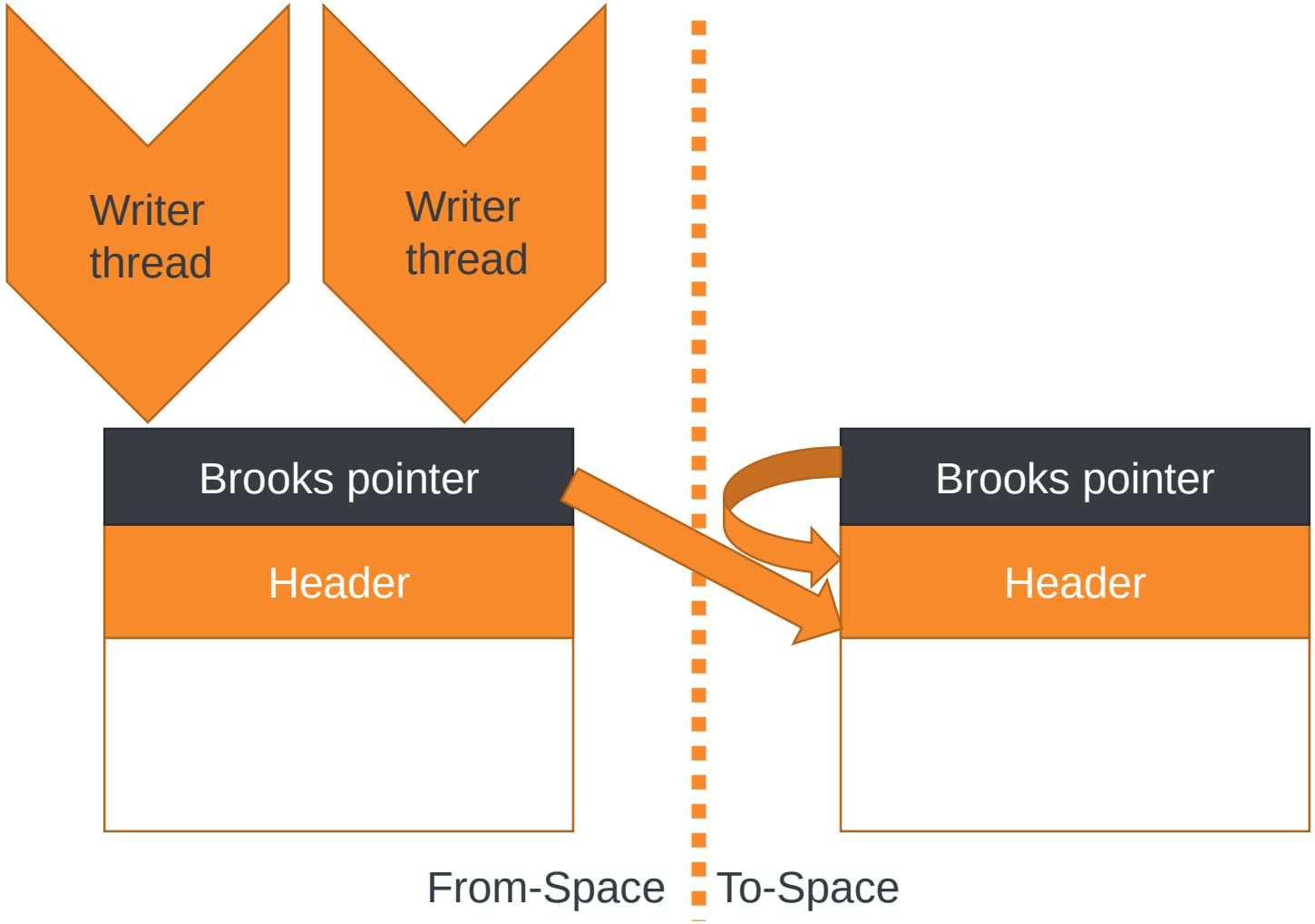

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Extreme cases

- Late memory release
  - Only happens when all refs updated (Concurrent Cleanup phase)
- Allocations can overrun the GC
- Failure modes:
  - Pacing
  - Degenerated GC
  - FullGC

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Shenandoah 2.0?

- Since JDK13, notable changes introduced

- Load Reference Barrier
  - Baker-style barrier (Relocation)
  - Evaluated at reference load time

- Eliminating forward pointer word
  - Store forward information into Mark word
  - Remove Brooks pointer

Azul's C4

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Continuously Concurrent Compacting Collector

- Generational (young & old)
- Region based (pages)
- Use Read Barrier: Loaded Value Barrier
- Self-Healing
  - Cooperation between mutator threads & GC threads
- Pauseless algorithm but implementation requires safepoints
- Pauses are most of the time < 1ms

LVB

- Baker-style based Barrier
  - move objects through forwarding addresses stored aside
  - Applied at load time, not when dereferencing
  - Fused marking & relocation state
- Ensure C4 invariants:
  - Marked Through the current cycle
  - Not relocated
- If not => Self-healing process to correct it
  - Mark object
  - Relocate & correct reference
- Checked for each reference loads
  - Benefits from JIT optimization for caching loaded value (registers)

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LVB

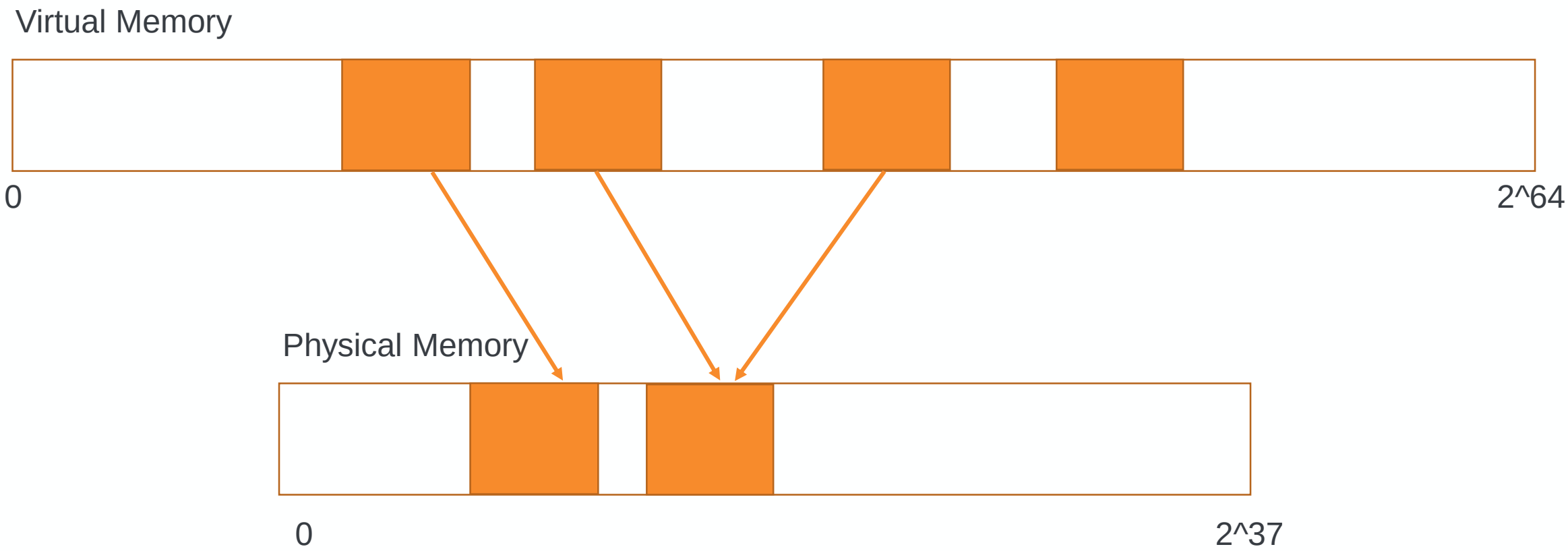
- States of objects stored inside reference address => Colored pointers
  - NMT bit
  - Remapped/Generation

- Checked against a global expected value during the GC cycle
  - Thread local, almost always L1 cache hits
  - Register

```
test    r9, rax
jne     0x3001443b
mov     r10d, dword ptr [rax + 8]
```

- Unmasking reference addresses:
  - Linux Kernel module, aliasing
  - memfd, multi-mapping

Virtual Memory vs Physical Memory



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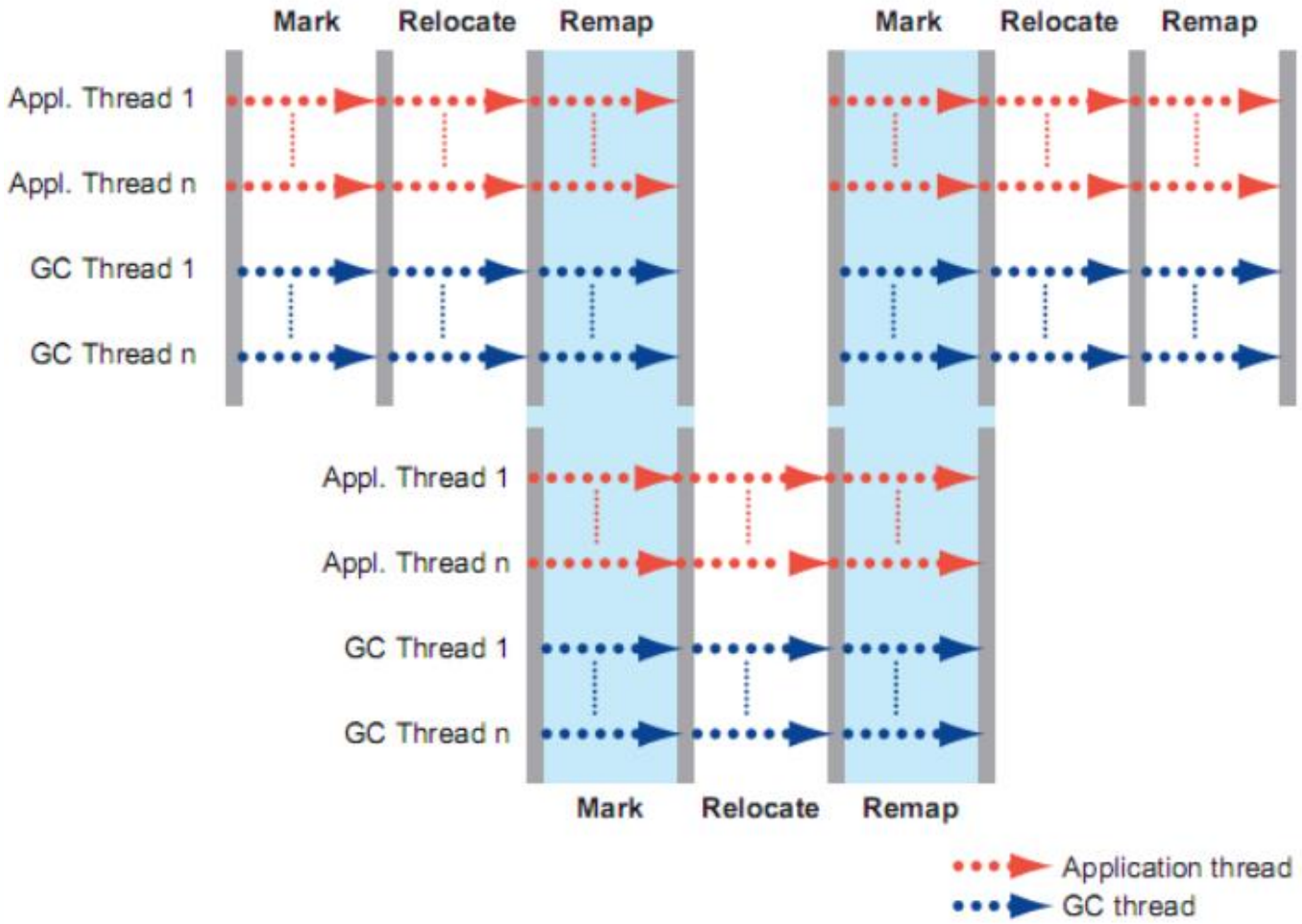
C4 Phases

- All phases are fully parallel & concurrent

- No "rush" to finish phases
  - No constraint about STW pause to be short
  - Physical memory released quickly in relocation phase
  - Can be reused for new allocations
  - Plenty of virtual space vs physical memory

C4 Phases

- Mark
  - Marking all objects in graph
- Relocation
  - Moving objects to release pages
- Remap
  - Fixup references in object graph
  - Folded with next mark cycle



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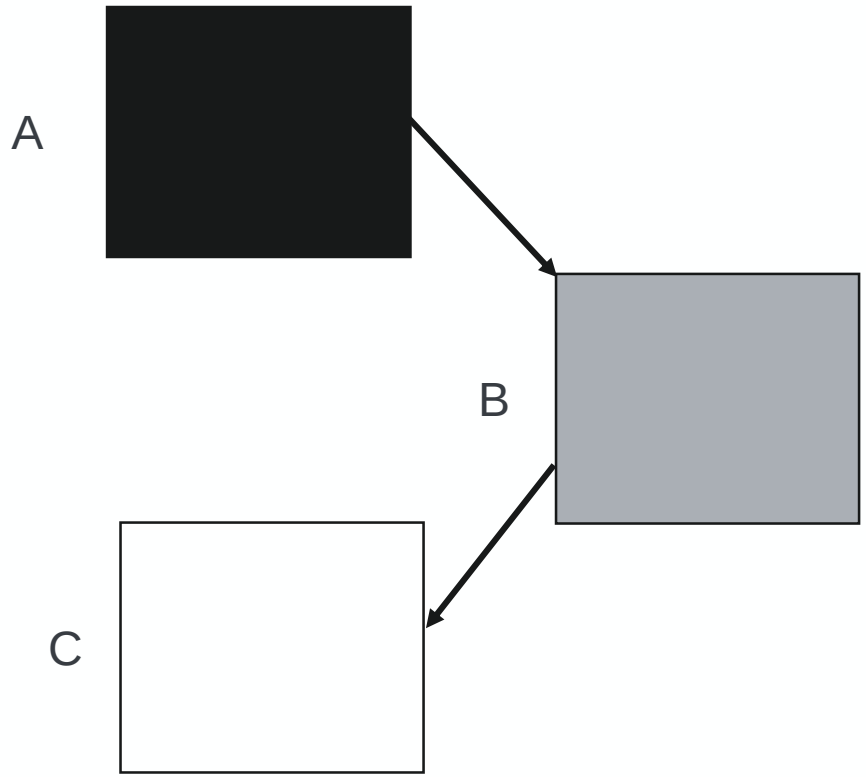
Mark Phase

- Precise Wavefront Marking
- Single pass
- No final mark/remark
- Self-Healing: Mark object that are not marked for the current cycle

Mark Phase: Concurrent Modification

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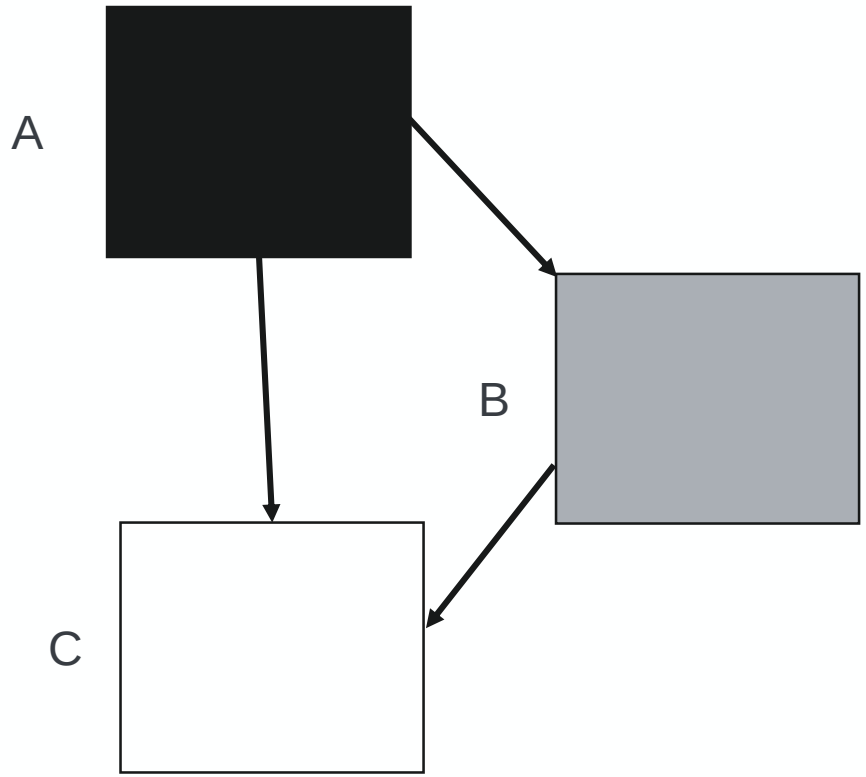


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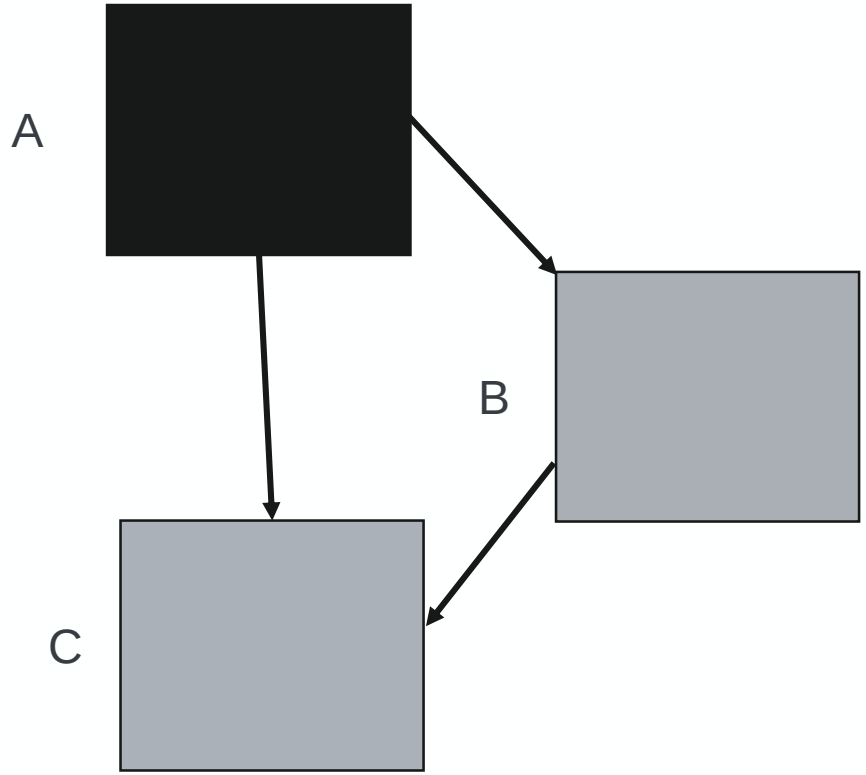

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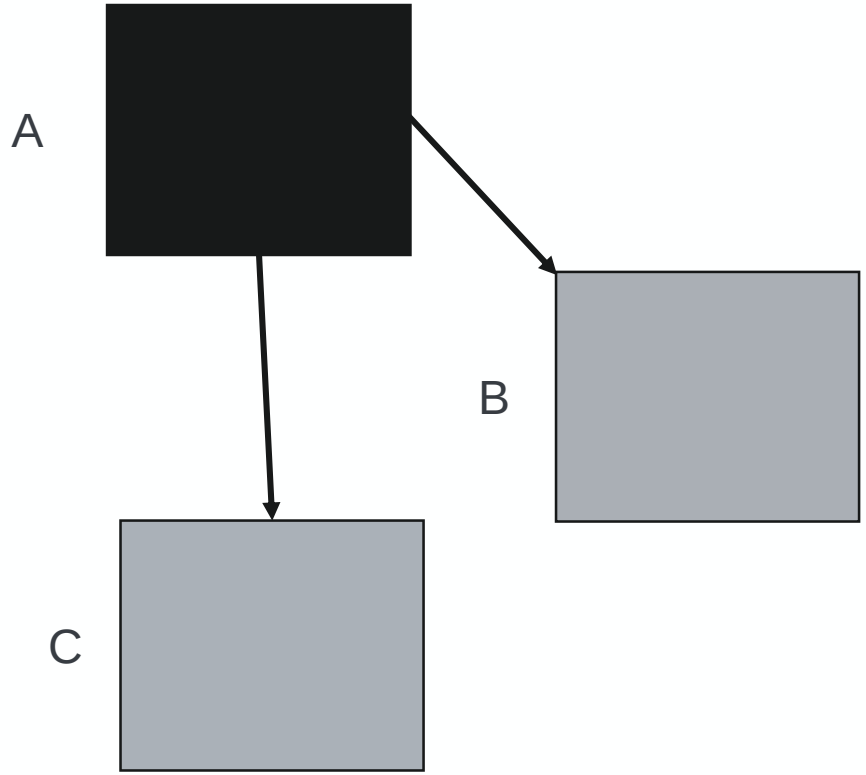

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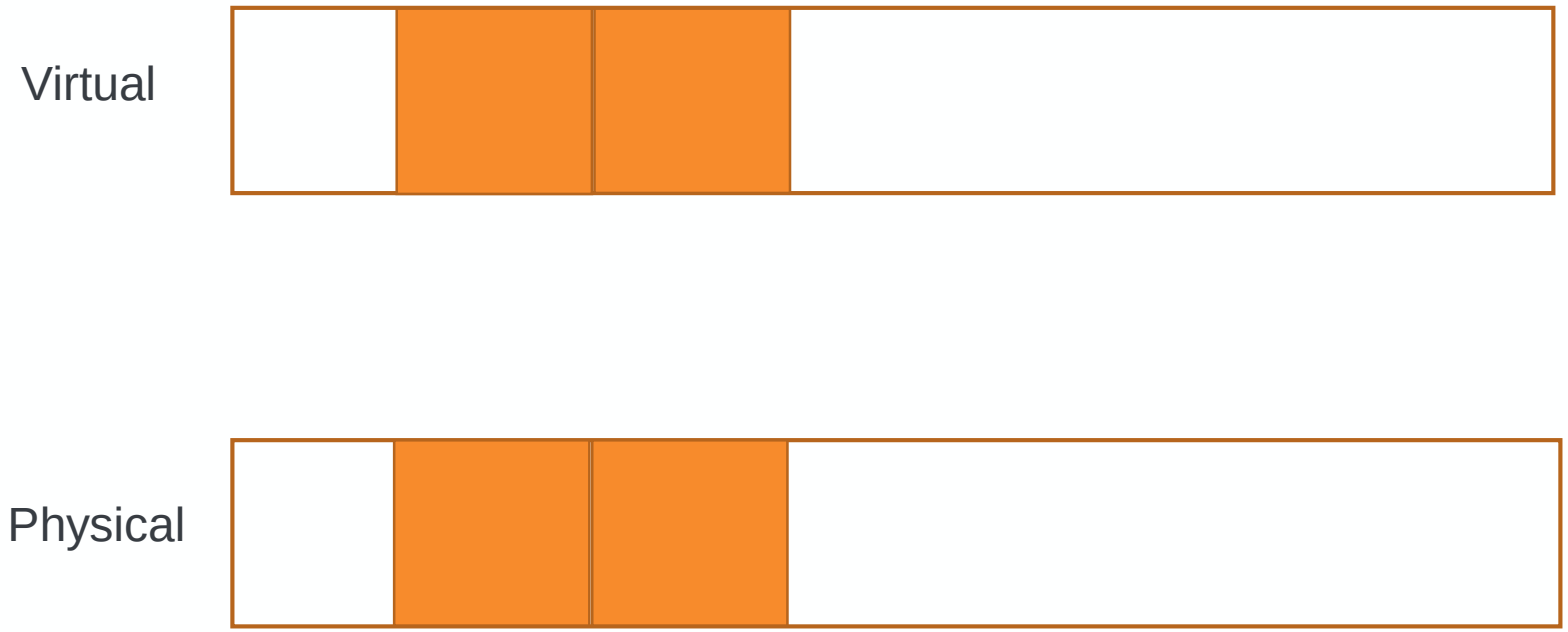
Mark Phase

- Scanning roots (Static var, Thread stacks, register, JNI handles)
  - GC threads scans stalled threads
  - Running threads scans their own stack stopping **individually** at Safepoint
- Scanning object graph like a parallel collector
- Newly allocated objects into new pages, not considered for reclaim (relocation)
- For each page, summing live data bytes, used to select page to reclaim

Relocation Phase

- Select pages with the greatest number of dead objects (garbage first!)
- Protect page selected from being accessed by mutators thread
- Move objects to new allocated pages
- Build side arrays (off heap tables) for forwarding information
- Self-Healing: As protected, LVB will trigger a trap to:
  - Copy object to the new location if not done
  - Use forward pointer to fix the reference

Relocation Phase



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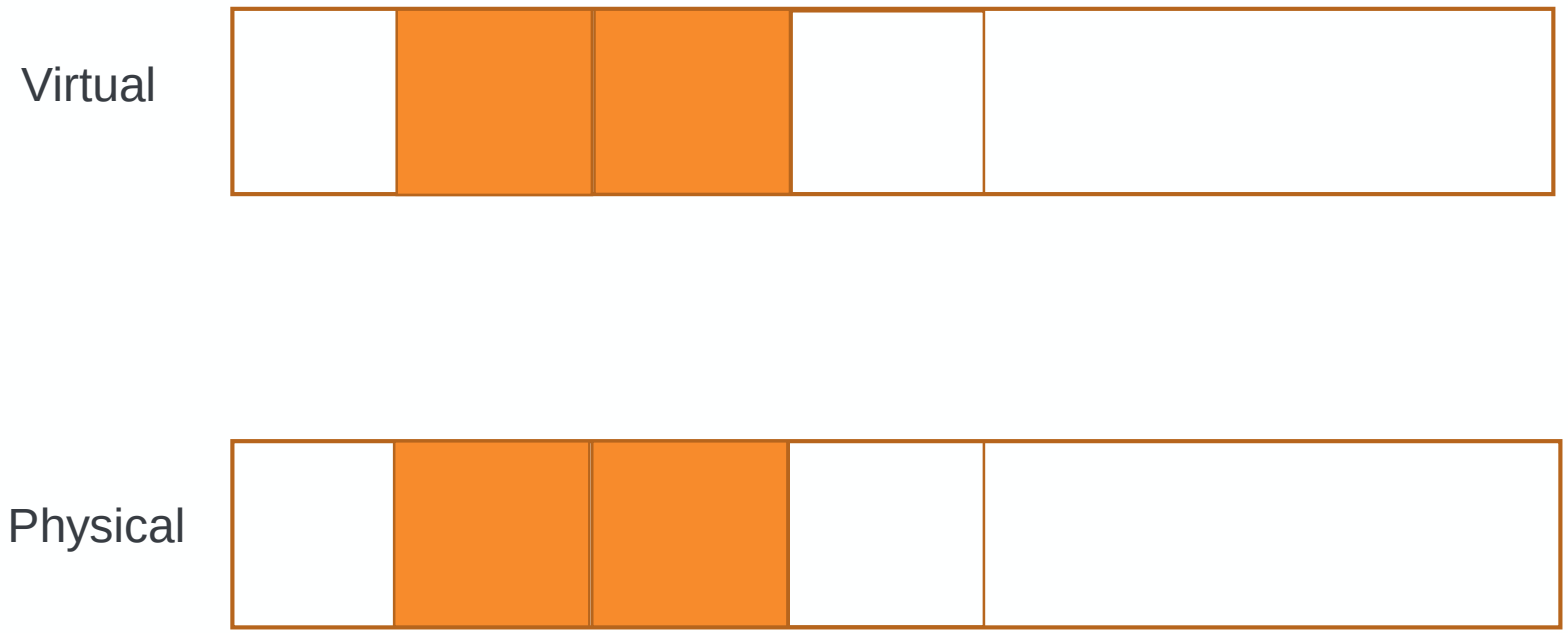

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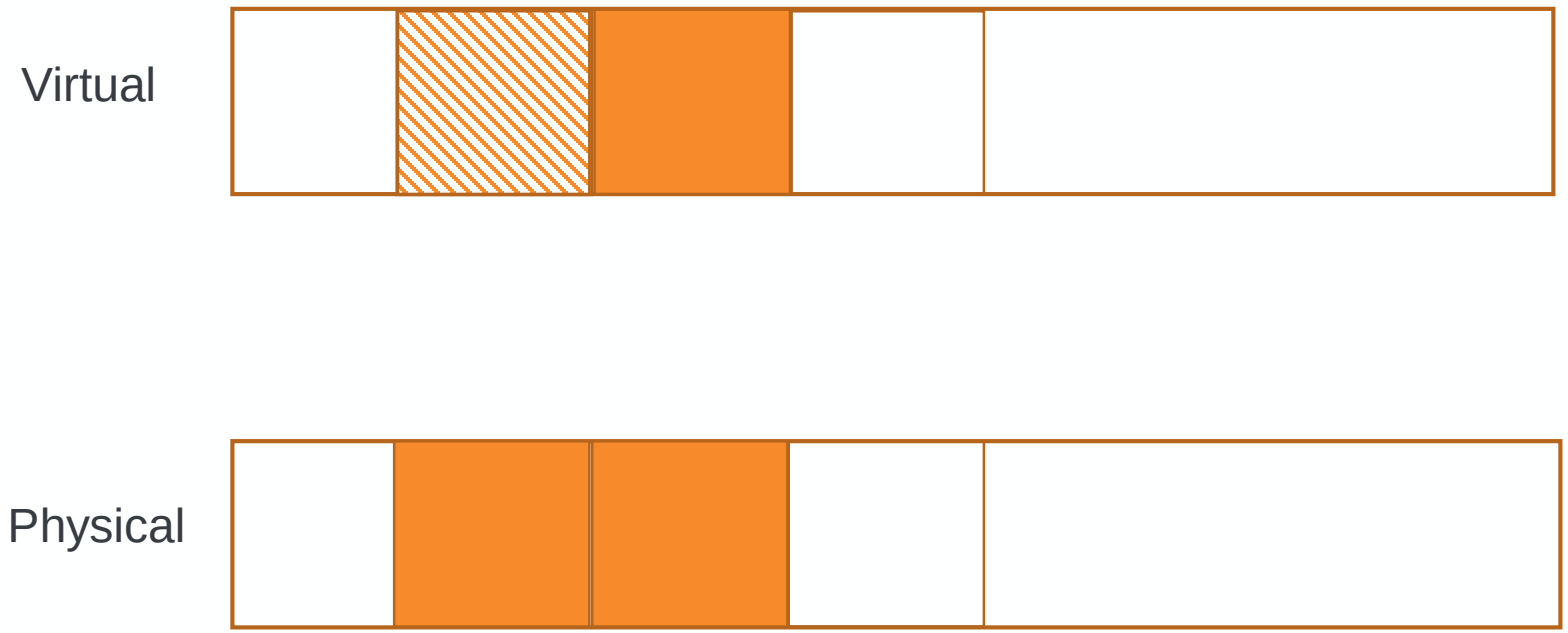

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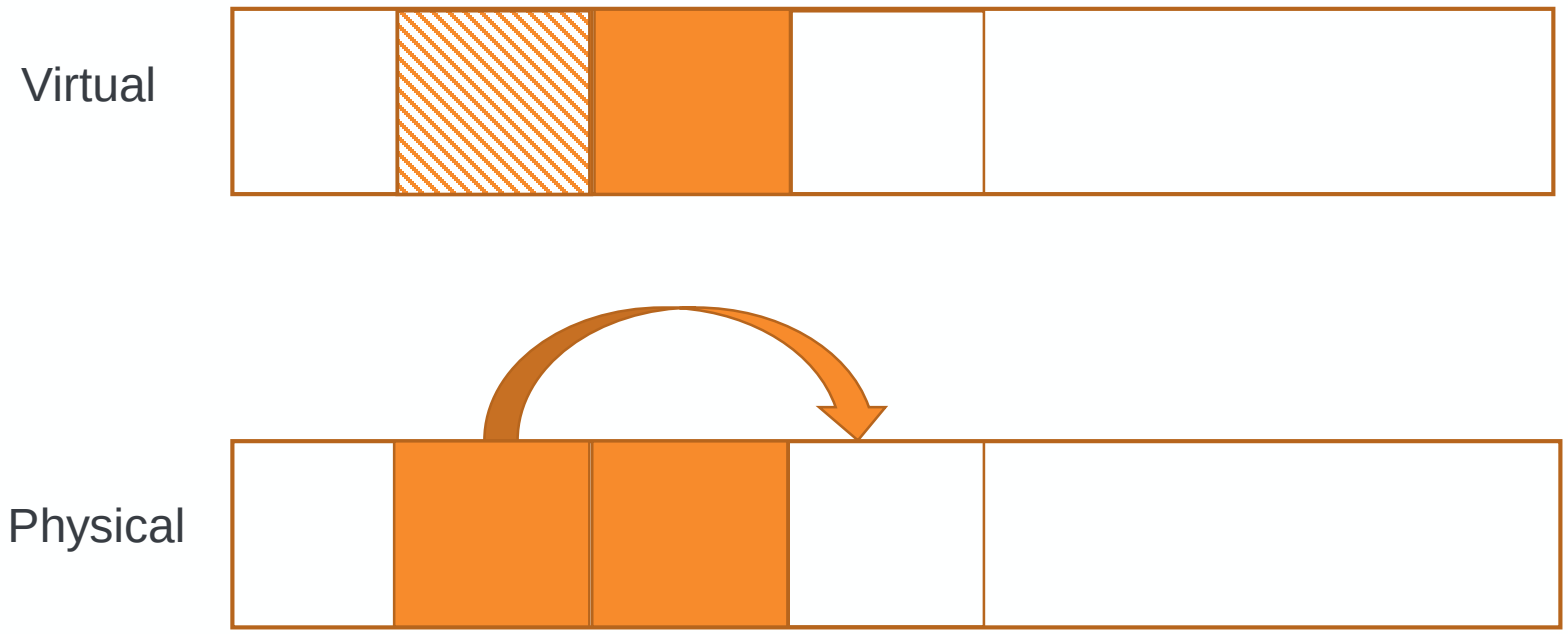

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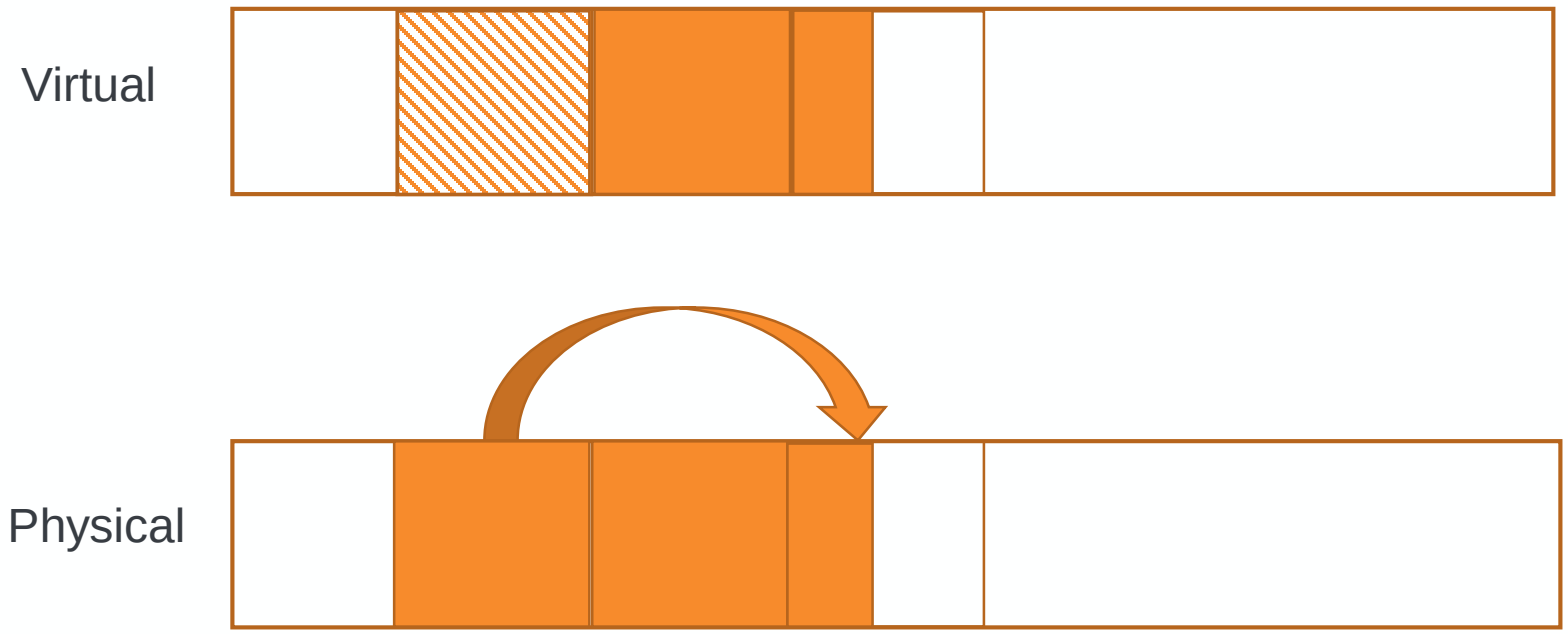

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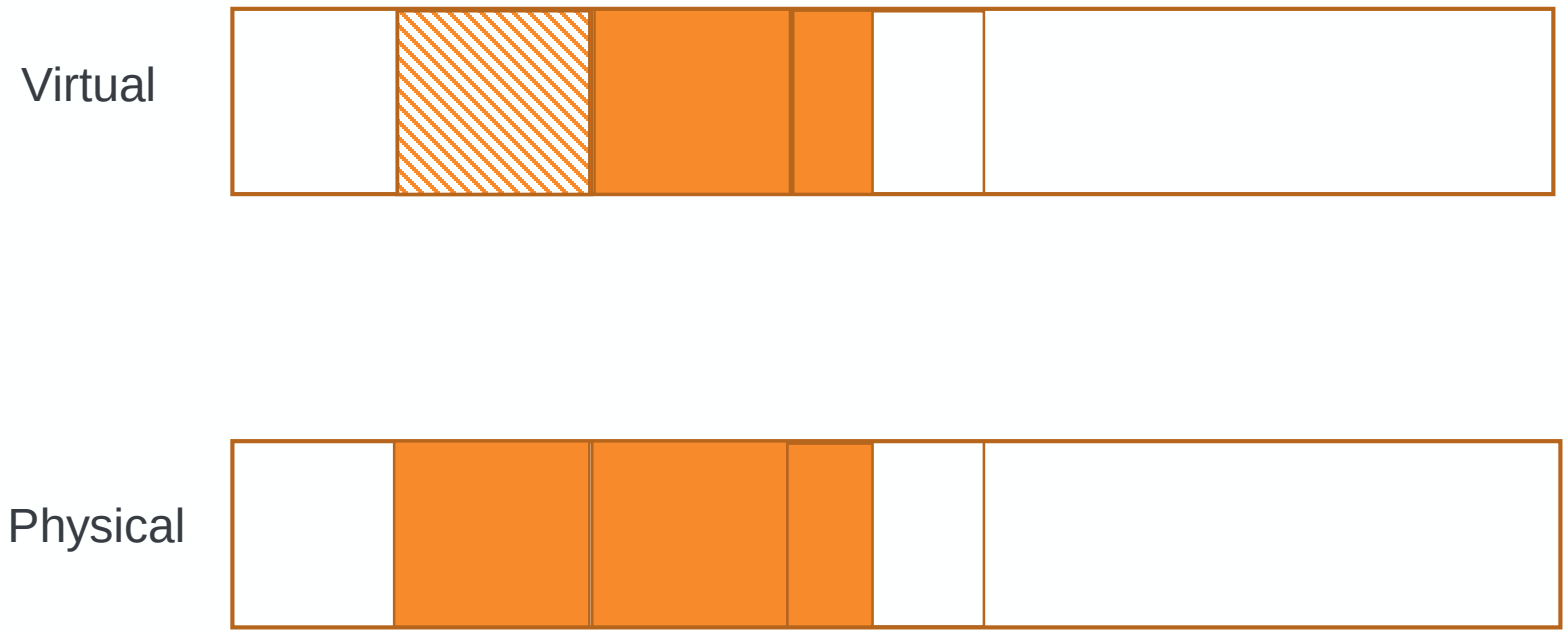

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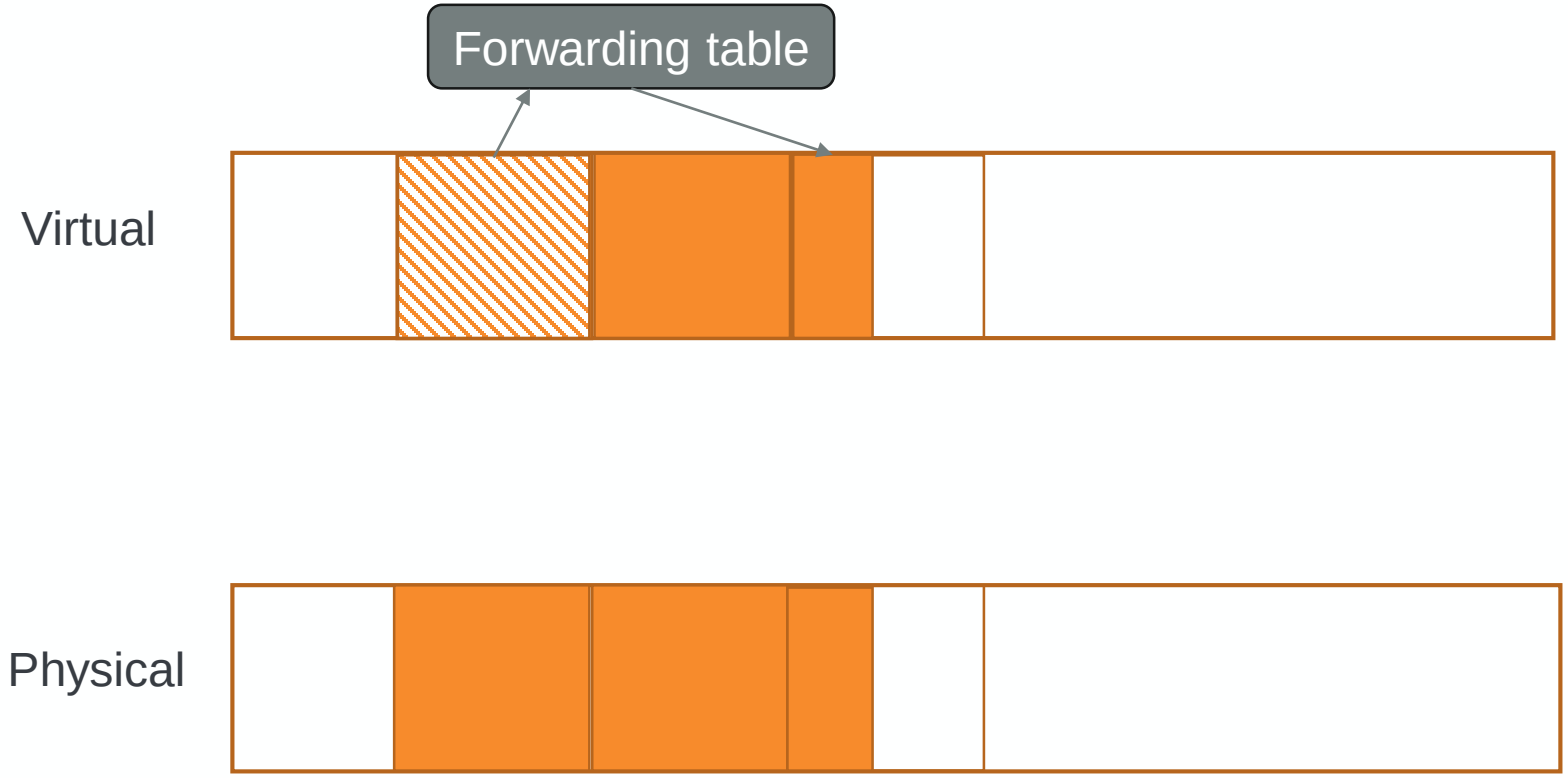

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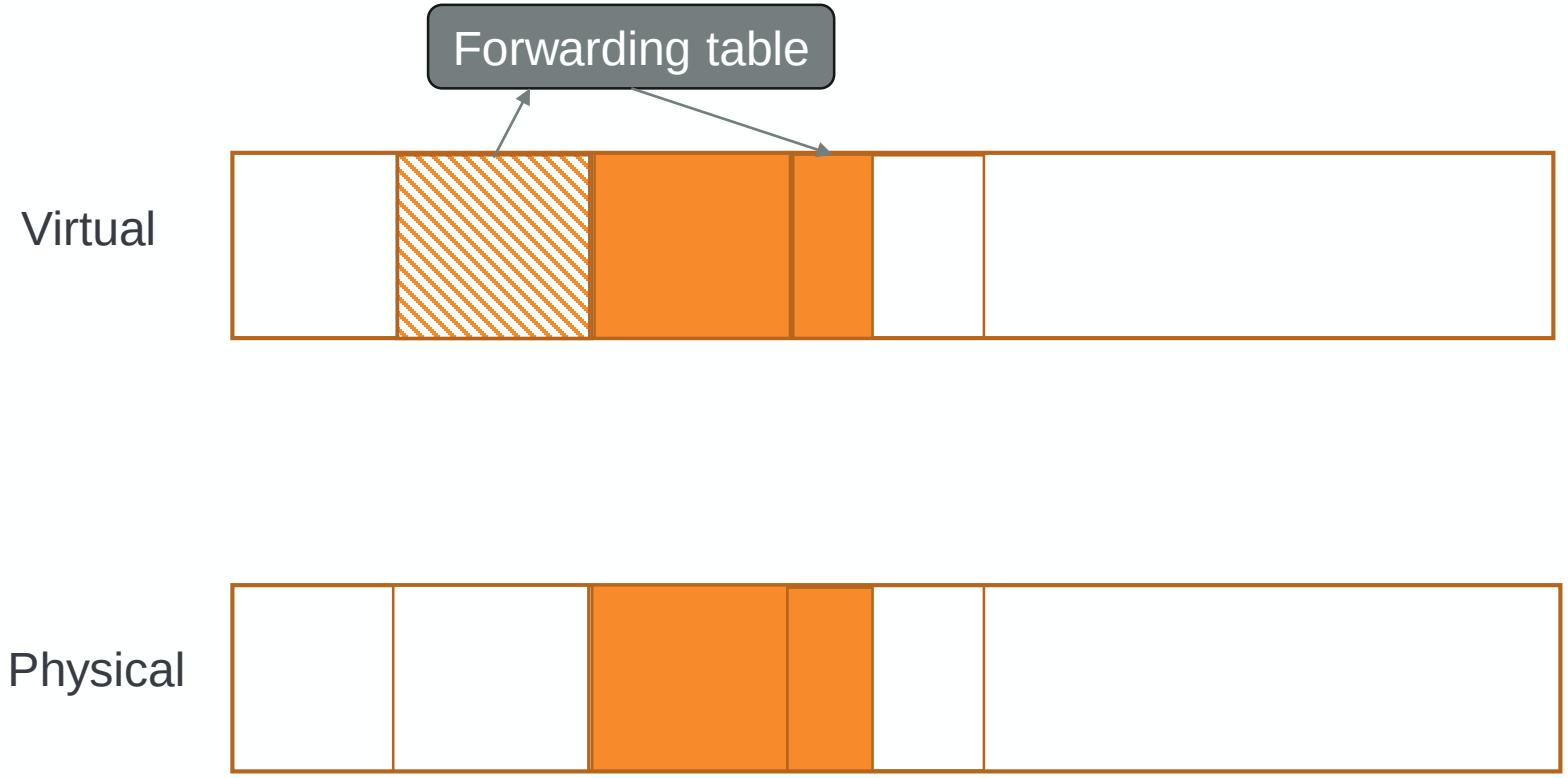

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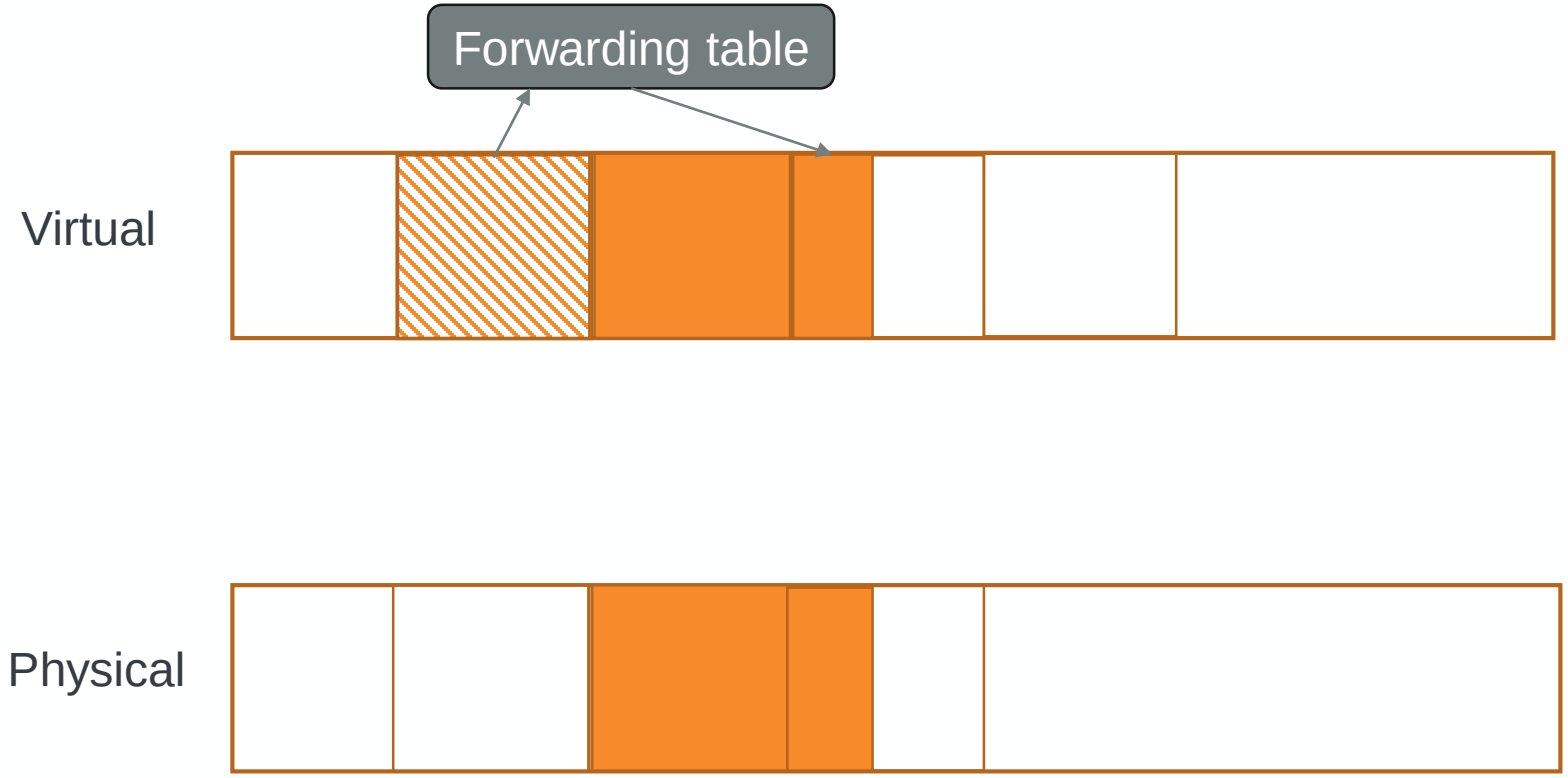

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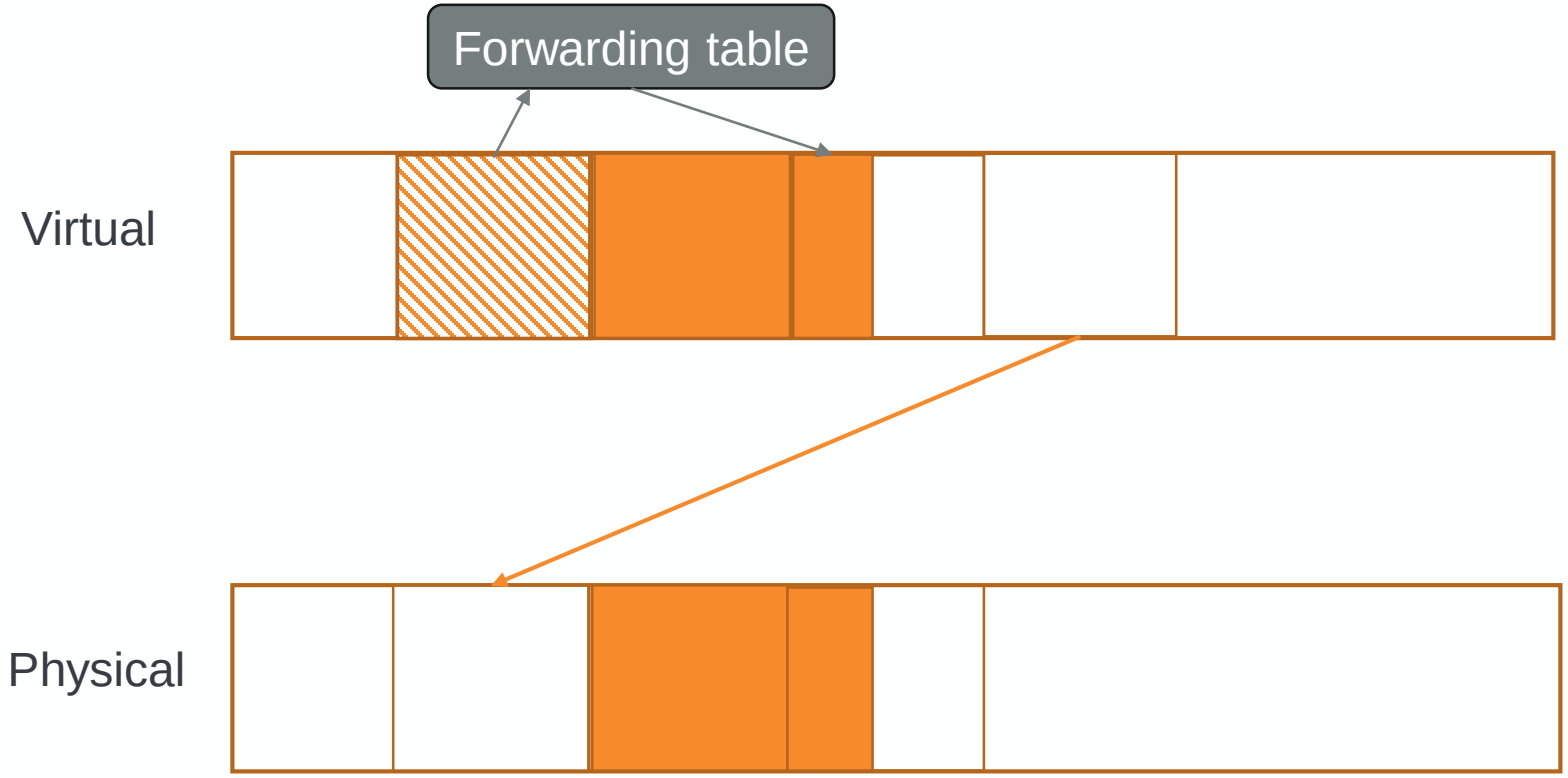

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Relocation Phase

- Few chances mutators stall on accessing a ref as processing mostly dead pages

- Once object copy done, physical memory is released (Quick Release)
  - Can be immediately reused (remapped) to satisfy new allocations

- Pages evacuated are still mapped & protected to help remap phase
  - Cannot be released until all objects are remapped
  - Not a problem as we have a **huge** virtual address space

Remap Phase

- Traverse Object Graph and fixup references
- Execute LVB barrier for each object
- Self-Healing: fixup references using forward information
- As we traverse again, mark for the next phase
  - Mark & Remap phases are folded!

Remap – Kernel module

- Algorithm requires a sustainable rate or remapping operations

- Linux limitations:
  - TLB invalidation
  - Only 4KB pages can be remapped
  - Single threaded remapping (write lock)

- Kernel module implements API for the Zing JVM to increase significantly the remapping rate

- Implements also virtual address aliasing for addressing objects with metadata

Generational

- Young & Old collections done by same algorithm and can be concurrent
- Size of the generation are dynamically adjusted
- Card Marking with write barrier (Stored Value Barrier)
- Old collection is based on young-to-old roots generated by previous young cycle
- Young collection will perform card scanning per page
  - hold an eventual concurrent Old collection per page scanned

C4 @ Criteo

- Used by Hadoop Name Node
- 580GB Heap
- Very hard to tune with G1
- No issue so far regarding GC since production roll out (Oct 2017)

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Z GC

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Z GC

- Non generational
- Region based (zPages, dynamically sized)
- Concurrent Marking, Compaction, Ref processing
- Use Colored Pointers & Read/Load Barrier

```
mov     r10,QWORD PTR [r11+0xb0]
test    QWORD PTR [r15+0x20],r10
jne     0x00007f9594cc54b5
```

- Self-Healing
  - Cooperation between mutator threads & GC threads
- Experimental in JDK 11 (`-XX:+UnlockExperimentalVMOptions -XX:+UseZGC`)

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Z GC

Cliff Click
@cliff_click

Abonné

Ok, quick read of ZGC and it basically screams "GPGC done by Oracle". Can anybody closer to the truth fill in any details?

Traduire le Tweet

22:41 - 27 sept. 2018

5 Retweets **12** J'aime

2 5 12

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Z GC phases:

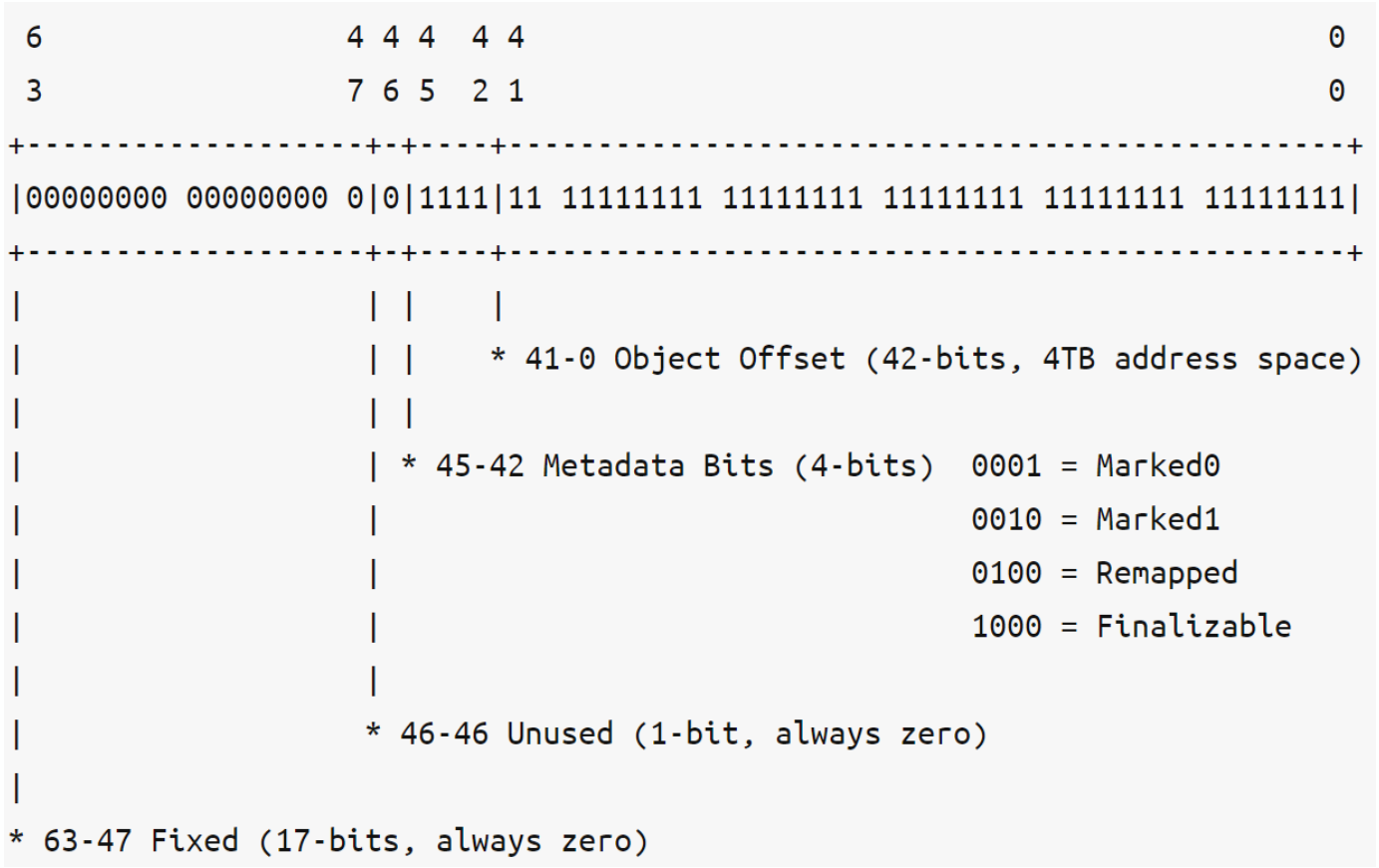
- Initial Mark (STW)
- Concurrent Mark/Remap
- Final Mark (STW)
- Concurrent Prepare for Relocation
- Start Relocate (STW)
- Concurrent Relocate

Colored Pointers

- Store metadata in unused bits of reference address

- 42 bits for addressing (4TB)
  - 44 bits (16TB) for JDK 13

- 4 bits for metadata
  - Marked0
  - Marked1
  - Remapped
  - Finalizable



Multi-Mapping

- Colored pointers needs to be unmasked for dereferencing
  - Some HW support masking (SPARC, Aarch64))
  - On linux/windows, overhead if done with classical instructions

- Only one view is active at any point

- Plenty of Virtual Space

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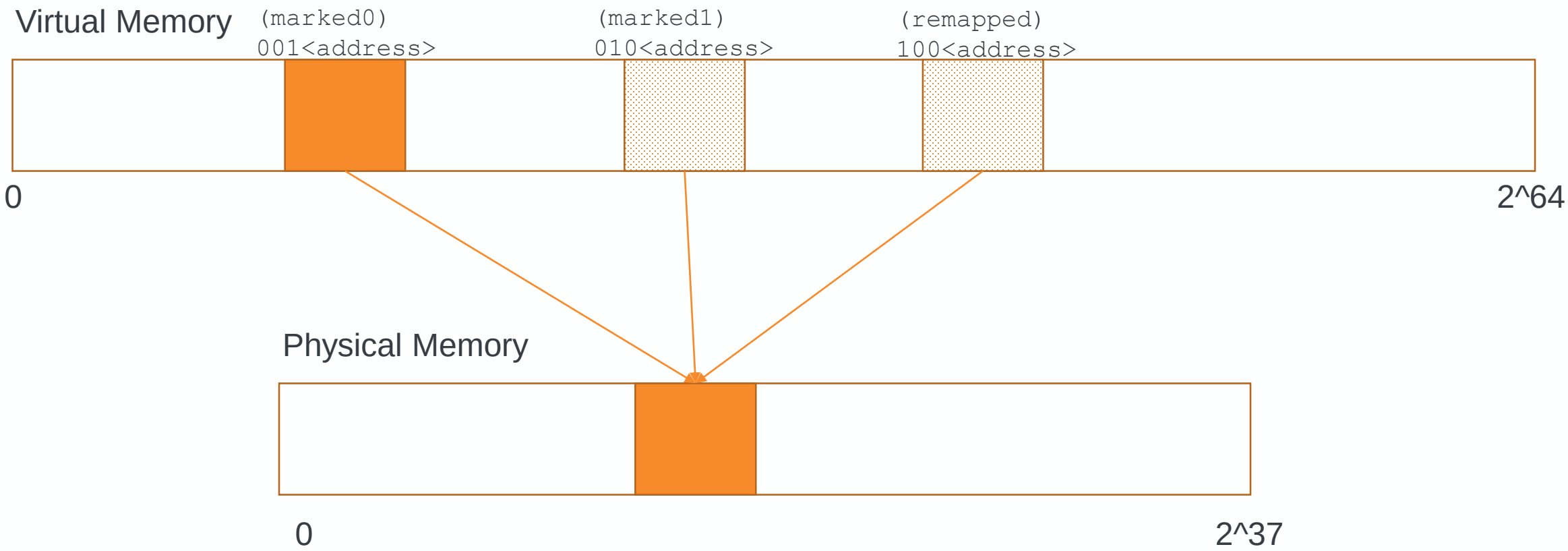
Multi-Mapping



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Memory Usage

Hi there,

I'm trying ZGC on trivial workloads, and I have a question about footprint. The workload runs with -Xms16g -Xms16g, but the RSS figures are at least 3x larger

```
VmPeak: 18256721392 kB
VmSize: 18256721392 kB
VmLck:         0 kB
VmPin:         0 kB
VmHWM:  50729036 kB
VmRSS:  50729036 kB
RssAnon:          369700 kB
RssFile:           27688 kB
RssShmem:       50331648 kB
```

Is this because ZGC maps the same physical space with multiple virtual mappings? Or is it a bug?

Thanks,
-Aleksey

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Page Allocations

- Pages are multiple of 2MB

- 3 different groups
  - Small: 2MB pages with object size <= 256KB
  - Medium: 32MB pages with object size <= 4MB
  - Large: 2MB pages, objects span over multiple of them

- Objects in Large group are meant to not to be relocated (too expensive)

Difference between C4 & Z GC

- Unmasking ref addresses
  - C4: Kernel module aliasing
  - Z: Multi-mapping or HW support

- Pages & Relocation
  - C4:
    - Page are fixed (2MB)
    - relocation for large objects by remapping
  - Z:
    - zPages are dynamic, a zPage can be 100MB large
    - No relocation for large objects

How to choose a GC algorithm

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Low latency GCs

- You have to run on Windows
  - Shenandoah
- Battlefield tested GC (maturity)
  - C4
  - Shenandoah
- Minimizing any kind of JVM pauses
  - C4
  - Z
- You don’t want pay for it:
  - Shenandoah
  - Z

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- The Pauseless GC algorithm (2005)
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- 2010 version source code

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- A first look into ZGC by Dominik Inführ
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- ZGC Heap Size and RSS counters

Thank You!

@jpbempel

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