TRASHTALK

EXPLORING THE MEMORY MANAGEMENT IN THE JVM

ABOUT ME.

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azul

MEMORY MANAGEMENT

IN THE JVM...

IS AUTOMATIC RIGHT...?

SO...WHY CARE...?

MEMORY MANAGEMENT

Why you should care…

-  Impact on application performance

MEMORY MANAGEMENT

Why you should care…

-  Impact on application performance
-  Impact on application responsiveness

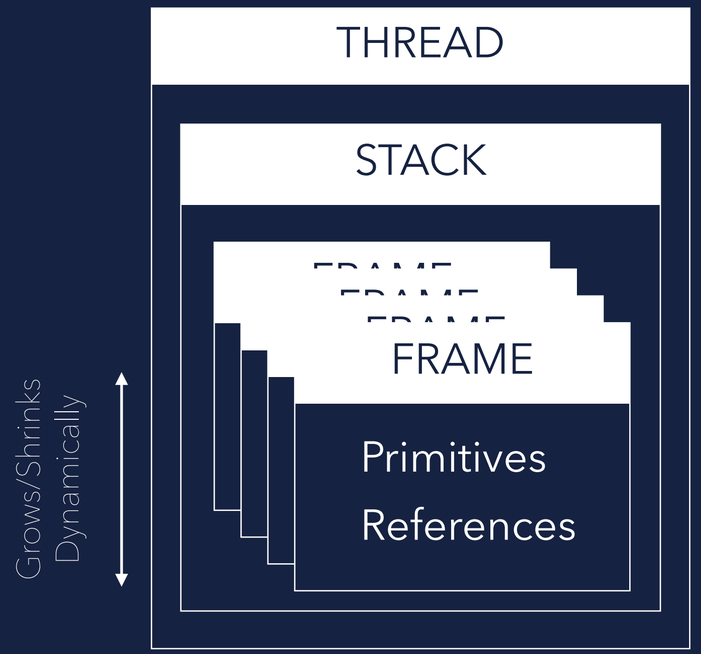
MEMORY MANAGEMENT

Why you should care…

-  Impact on application performance
-  Impact on application responsiveness
-  Impact on system requirements

MEMORY MANAGEMENT

Stack, Heap and Metaspace



Local access -> thread safe

MEMORY MANAGEMENT

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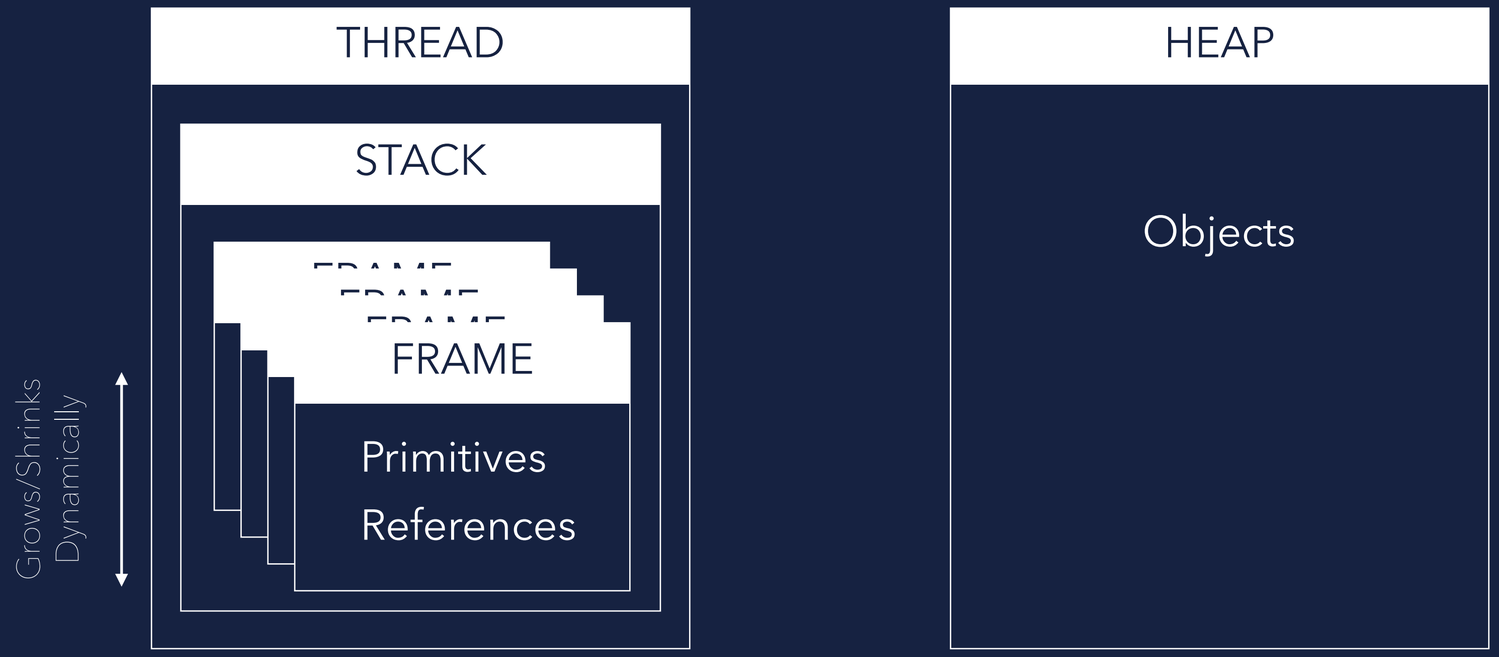

Local access -> thread safe

Shared access -> Not thread safe
Needs Garbage Collection

MEMORY MANAGEMENT

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Contains info needed for
JVM to work with classes

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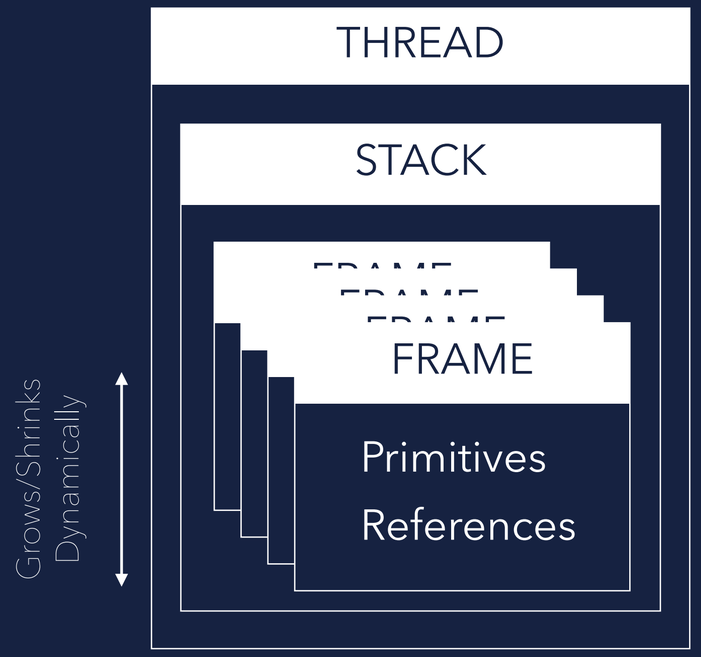
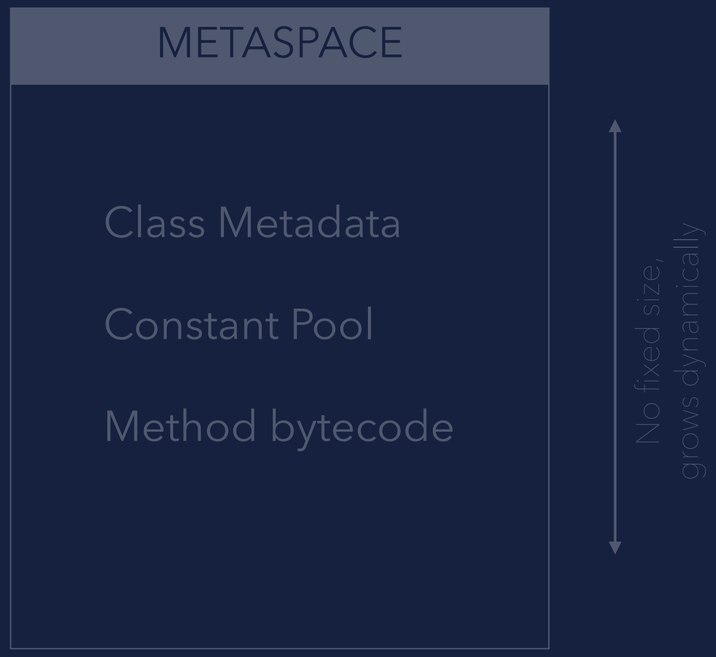


Local access -> thread safe

StackOverflowError

Shared access -> Not thread safe
Needs Garbage Collection

OutOfMemoryError



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MEMORY MANAGEMENT

In the JVM…

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public static void main(String[] args) {

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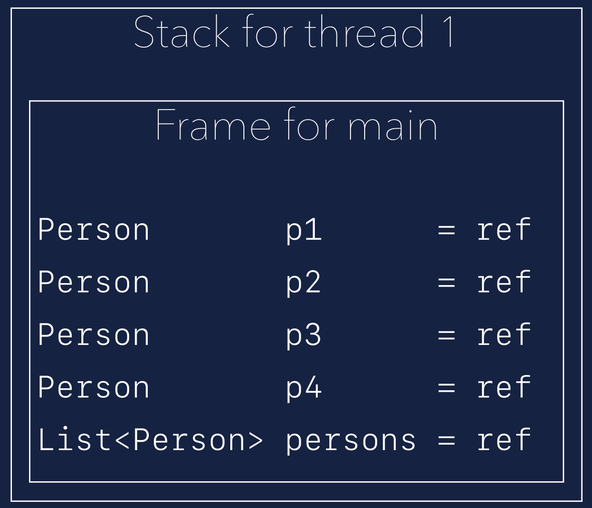

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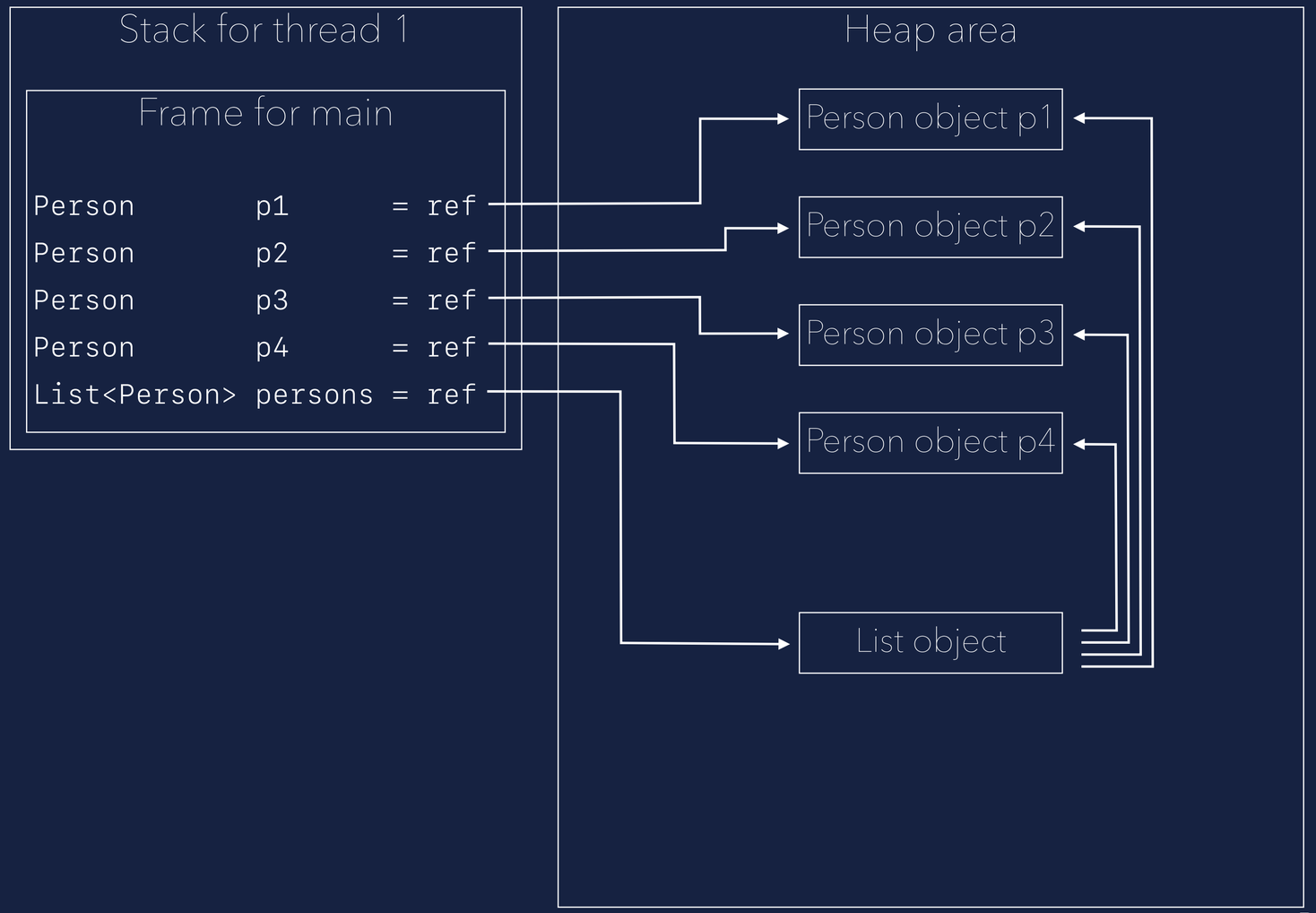

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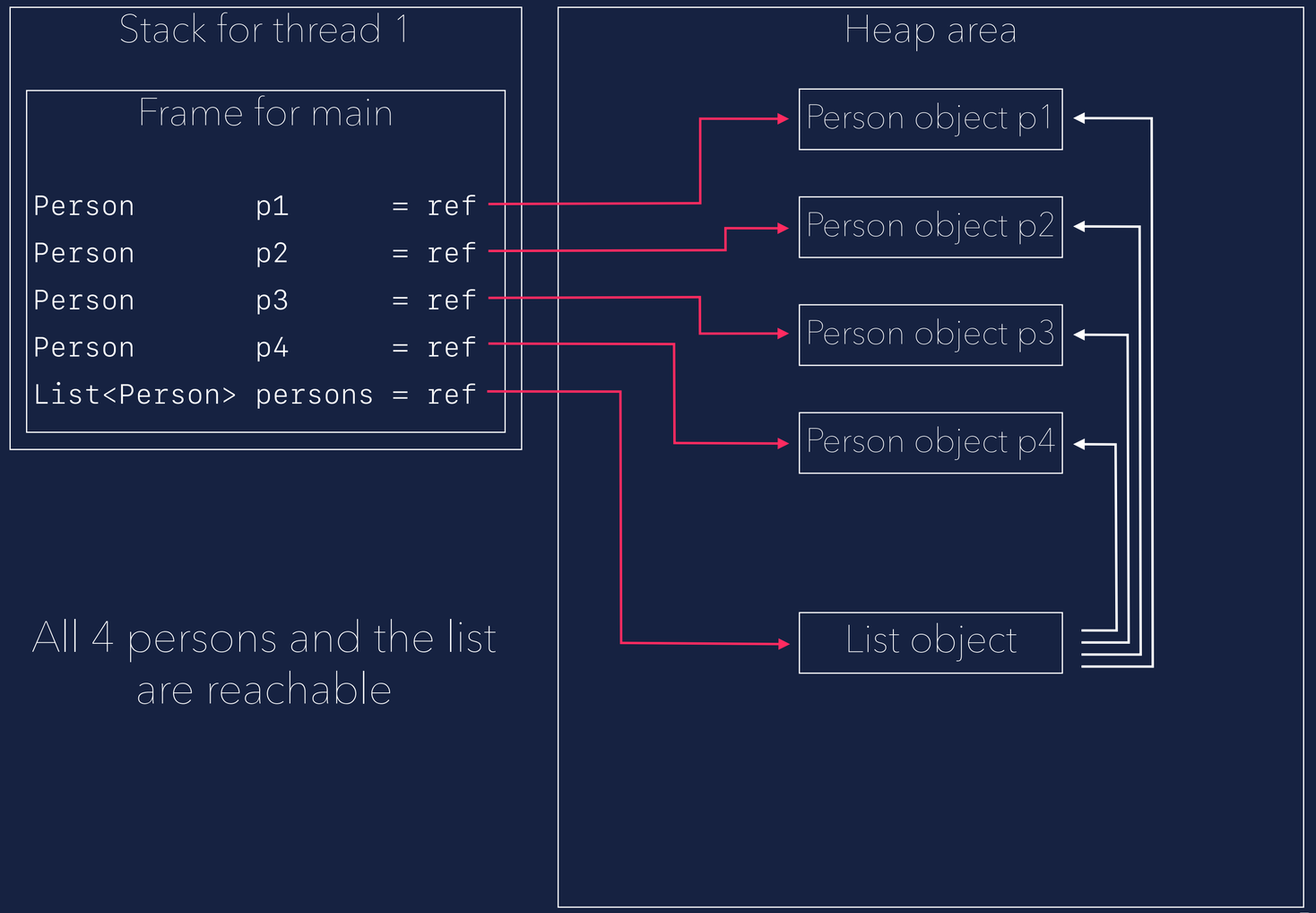

All 4 persons and the list are reachable

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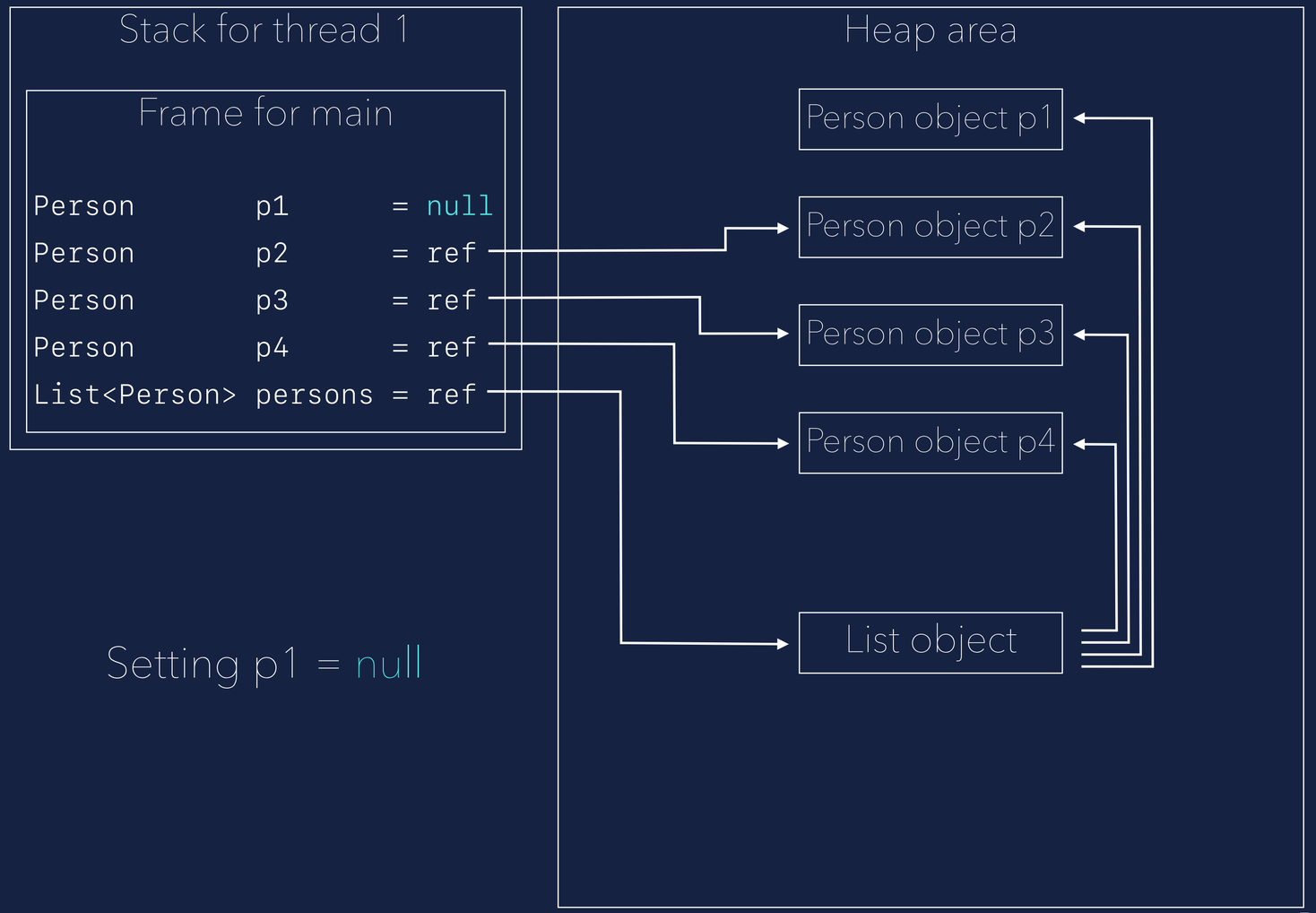

Setting p1 = null

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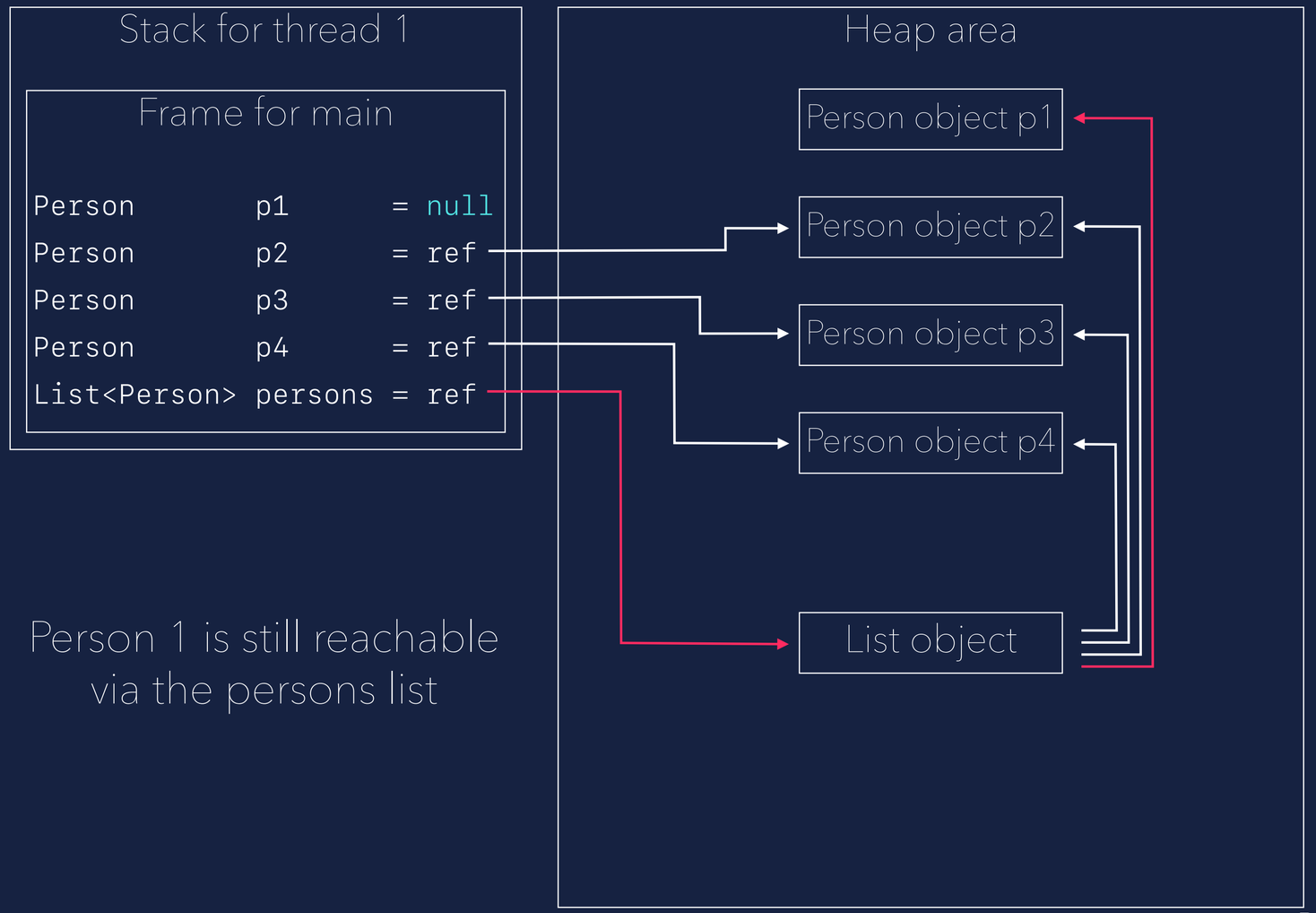

Person 1 is still reachable via the persons list

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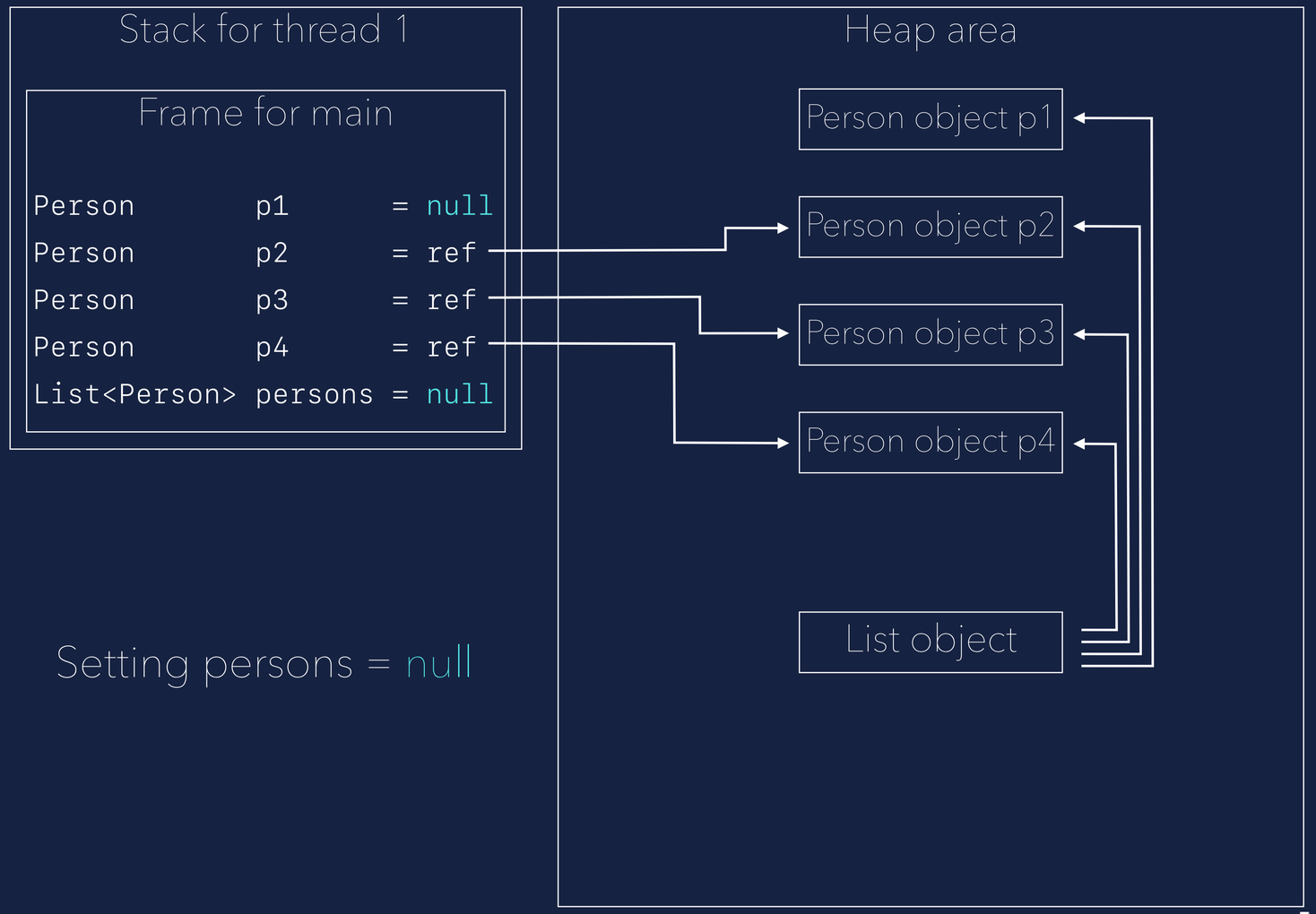

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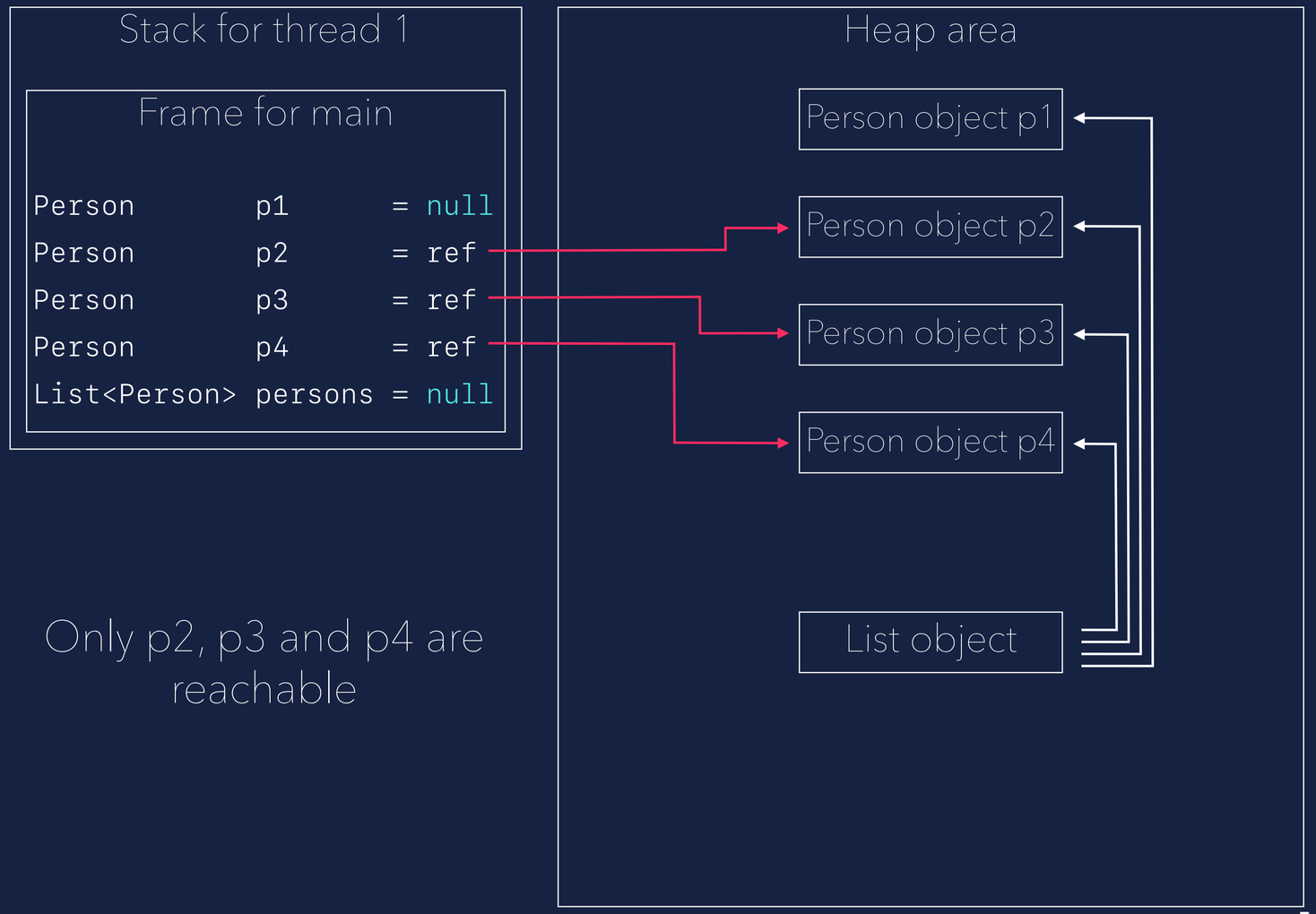

Only p2, p3 and p4 are reachable

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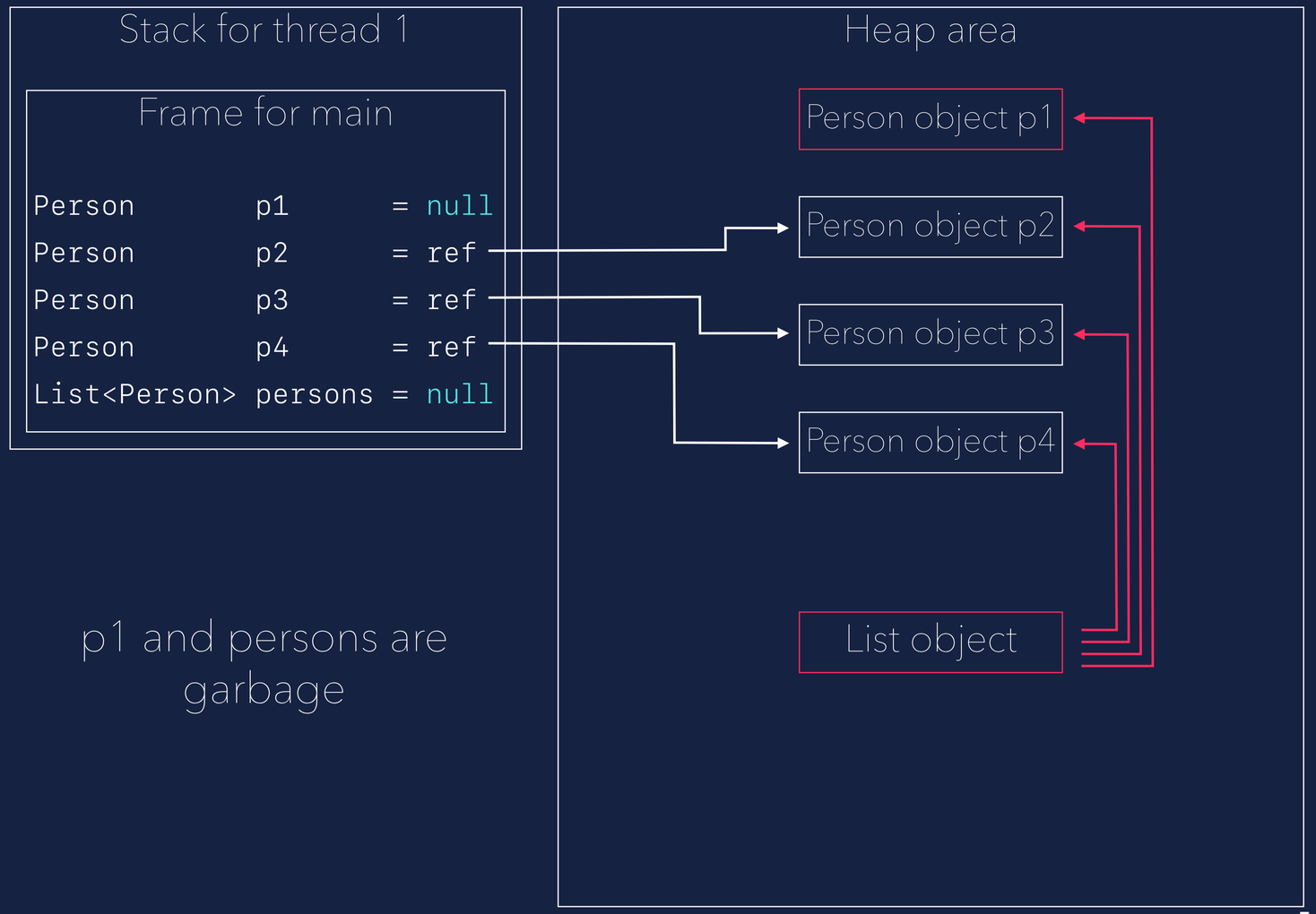

HOW TO GET RID OF IT...?

GARBAGE COLLECTION

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What is it…

-  Form of automatic memory management

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- Identifies and reclaims no longer used memory

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- Ensures efficient memory utilisation

GARBAGE COLLECTION

What is it…

- Form of automatic memory management
- Identifies and reclaims no longer used memory
- Ensures efficient memory utilisation
- Frees user from managing the memory manually

CONSERVATIVE AND PRECISE

GARBAGE COLLECTION

Conservative and Precise

- Conservative does not fully identify all object references
  (assumes any bit pattern in memory could be a reference, lead to more false positives)

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Conservative and Precise

- Conservative does not fully identify all object references
  (assumes any bit pattern in memory could be a reference, lead to more false positives)
- Precise correctly identifies all references in an object
  (needed in order to move objects)

PHASES

(precise collectors)

GARBAGE COLLECTION

Phases (precise collectors)

-  Tracing
  Identify live objects on the heap

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GARBAGE COLLECTION

Phases (precise collectors)

- Tracing
  Identify live objects on the heap
- Freeing
  Reclaim resources held by dead objects

GARBAGE COLLECTION

Phases (precise collectors)

Tracing

Identify live objects on the heap

Freeing

Reclaim resources held by dead objects

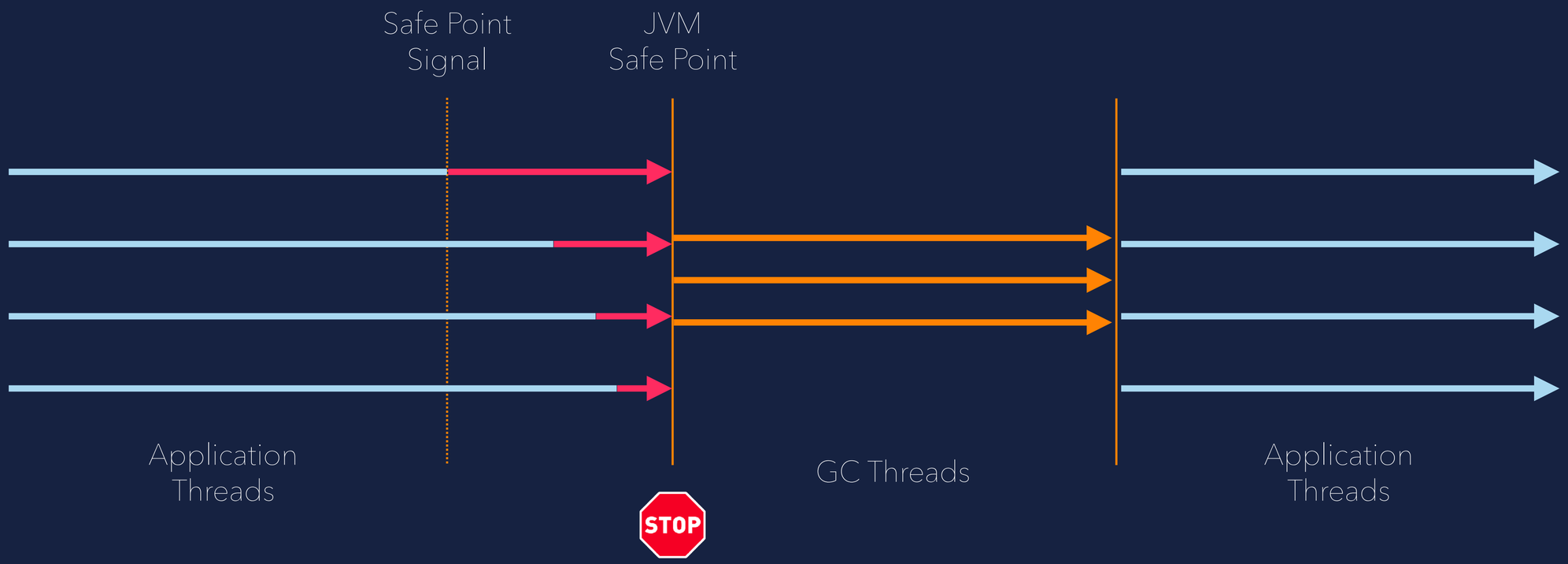
Compaction

Periodically relocate live objects

STOPPING THE WORLD

STOPPING THE WORLD

Halt of all application threads



COLLECTORS

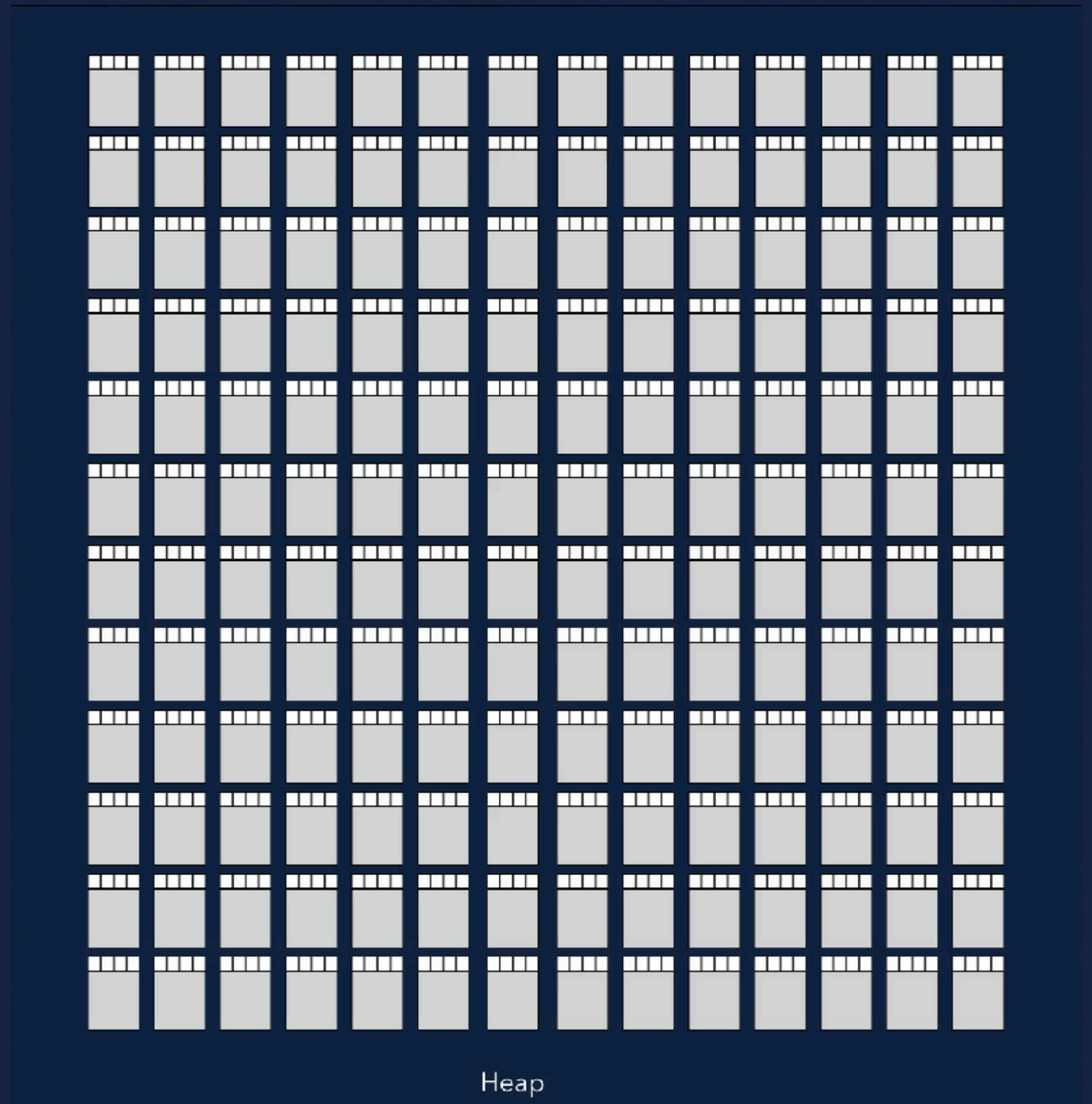
NON MOVING COLLECTOR

Mark & Sweep

NON MOVING COLLECTOR

Demo

1. Mutator allocates cells in Heap
2. Heap is out of memory -> GC
3. Mark all live cells
4. Free all dead cells
5. Unmark all live cells
6. Resume Mutator



Free Cell

Referenced Cell

Dereferenced Cell

Marked Cell

Referenced Cell (survived 1 GC)

Fragmentation

MOVING COLLECTORS

Compacting Collector & Copy Collector

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COMPACTING COLLECTOR

Mark & Compact

COMPACTING COLLECTOR

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6. Compact all live cells
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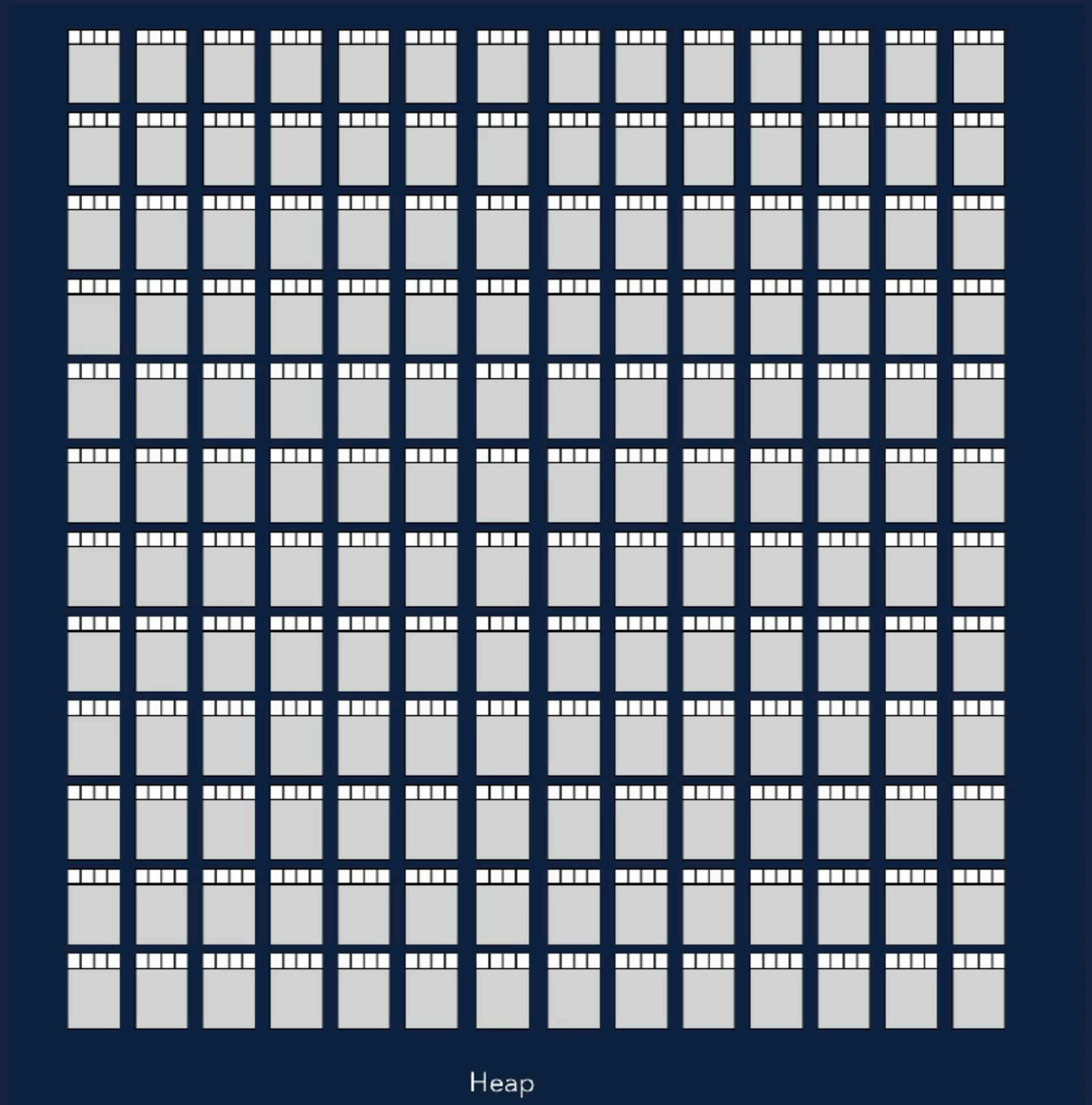


Free Cell

Referenced Cell

Dereferenced Cell

Marked Cell

Referenced Cell (survived 1 GC)

Easy allocation through
"Bump the pointer" technique

Headroom
20-50%

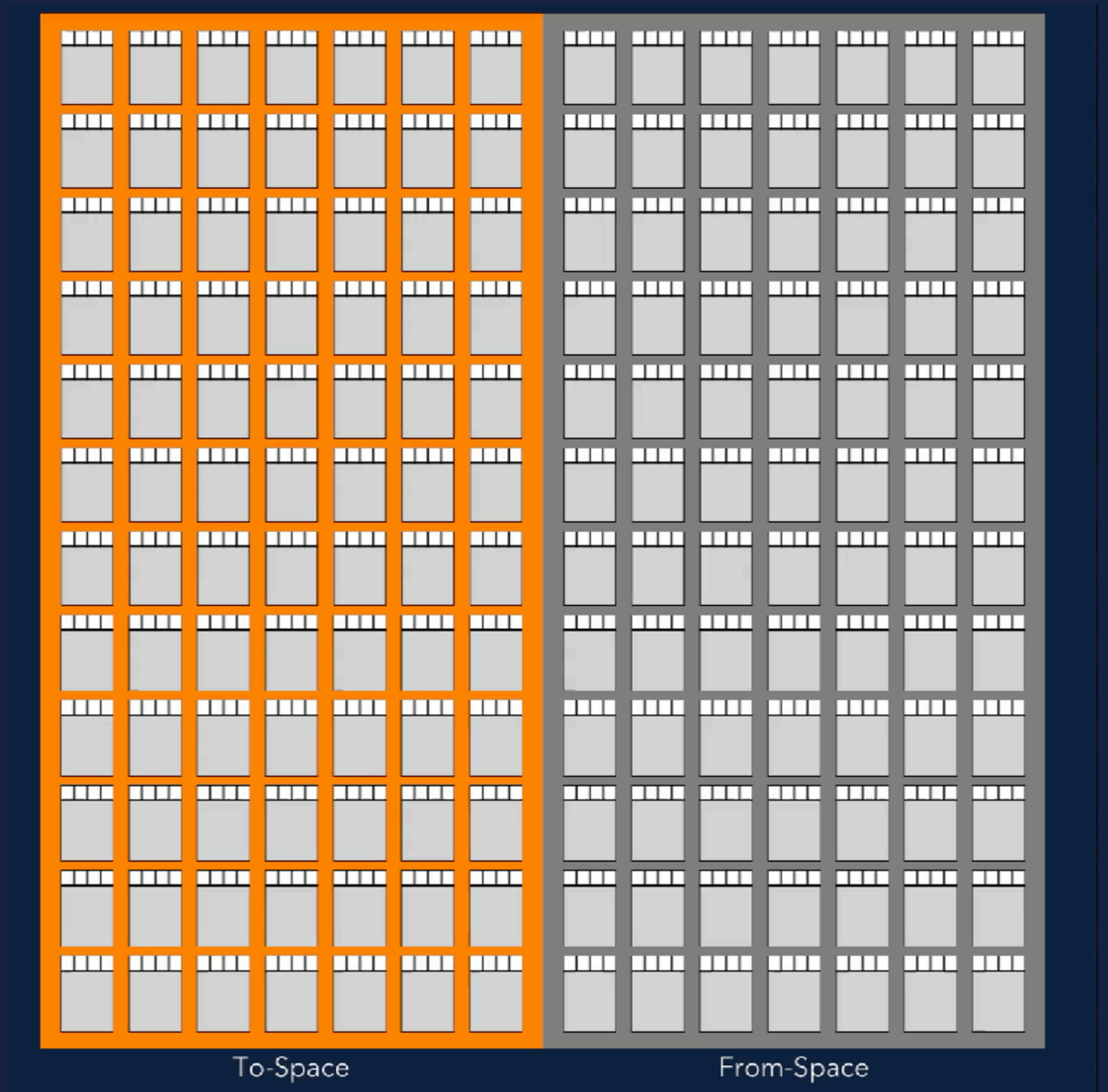
COPY COLLECTOR

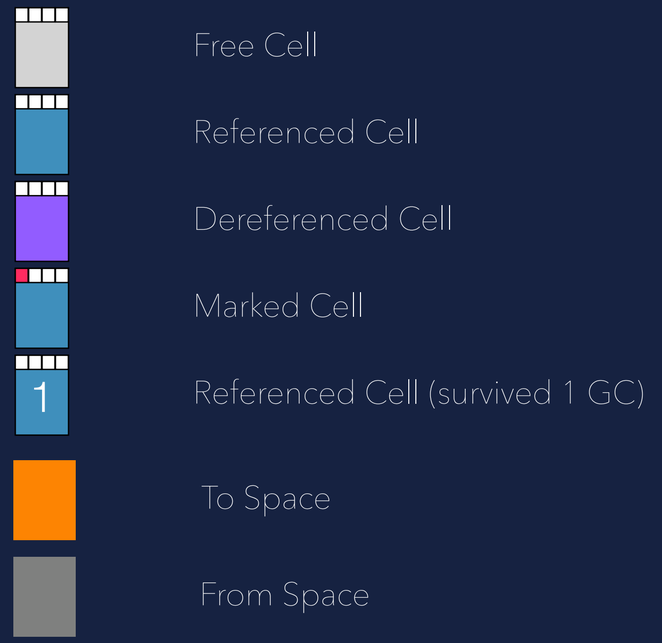
Mark & Copy

COPY COLLECTOR

Demo

1. Allocating in ToSpace
2. ToSpace is out of memory -> GC
3. Toggle To- and FromSpace
4. Mark live cells in FromSpace
5. Copy live cells to ToSpace
6. Free all cells in FromSpace
7. Resume Mutator





Long living objects and twice as much memory

GENERATIONAL COLLECTOR

Generational Mark & Compact

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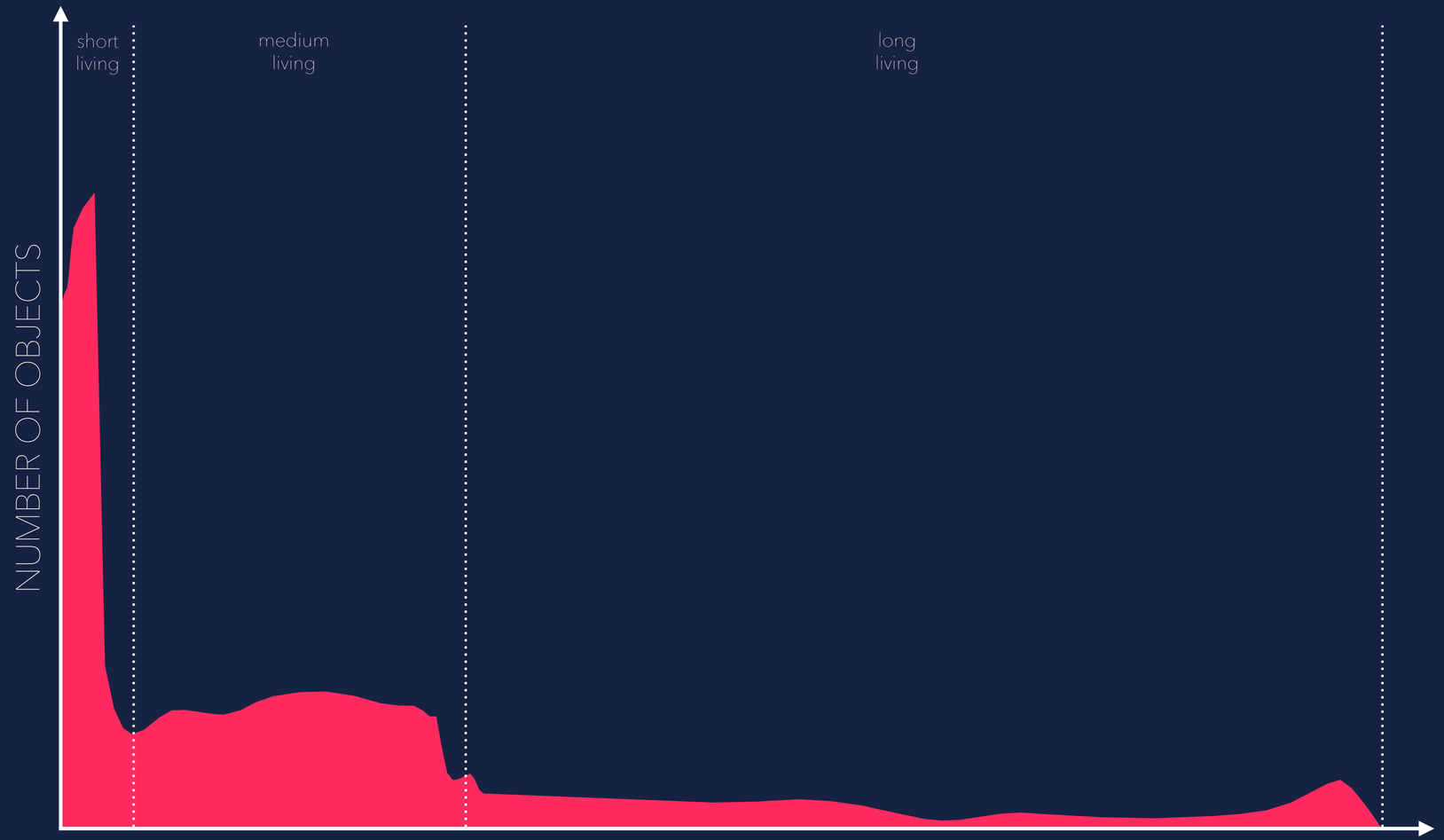
GENERATIONAL COLLECTOR

Weak Generational Hypothesis (Most objects die young)



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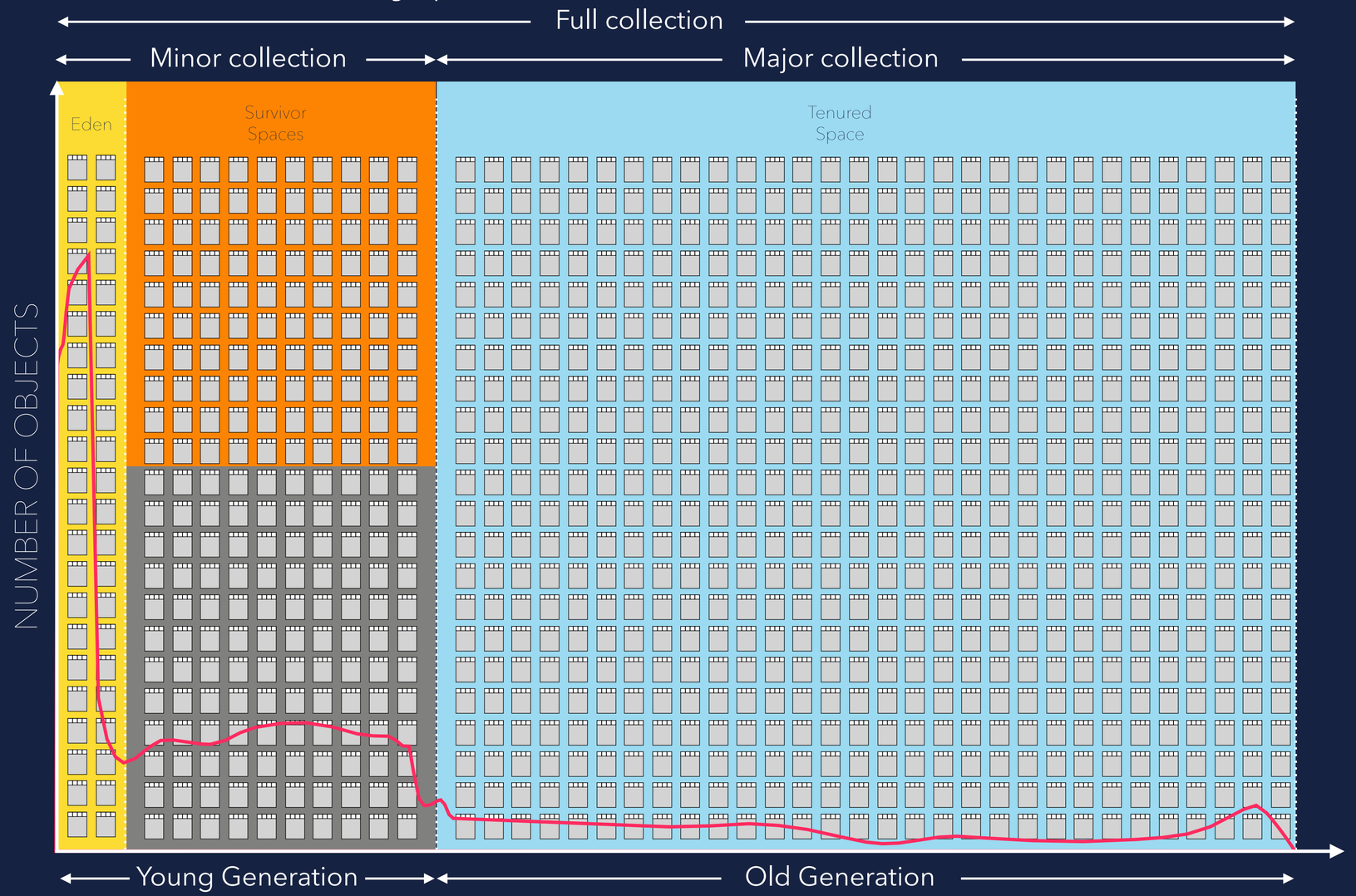
GENERATIONAL COLLECTOR

Weak Generational Hypothesis (Most objects die young)

Eden space for short living objects (can be collected quickly)

Survivor spaces for medium living objects

Tenured space for long living objects



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GENERATIONAL COLLECTOR

Demo

1. Mutator allocates cells in Eden
2. Eden is out of memory -> GC
3. Toggle To- and FromSpace
4. Copy all live cells from FromSpace to ToSpace
5. Copy all live cells from Eden to ToSpace
6. Promote live cells from FromSpace to TenuredSpace
7. Free all dead cells
8. Resume Mutator

Free Cell

Referenced Cell

Dereferenced Cell

Marked Cell

Referenced Cell (survived 1 GC)

Eden Space

To Space

From Space

Tenured Space

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REMEMBERED SET

Intergenerational References

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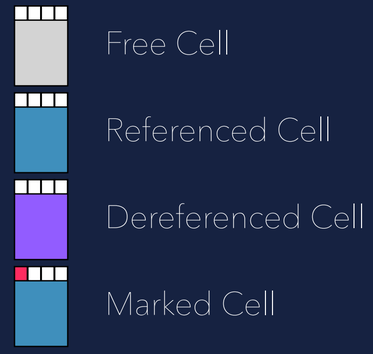
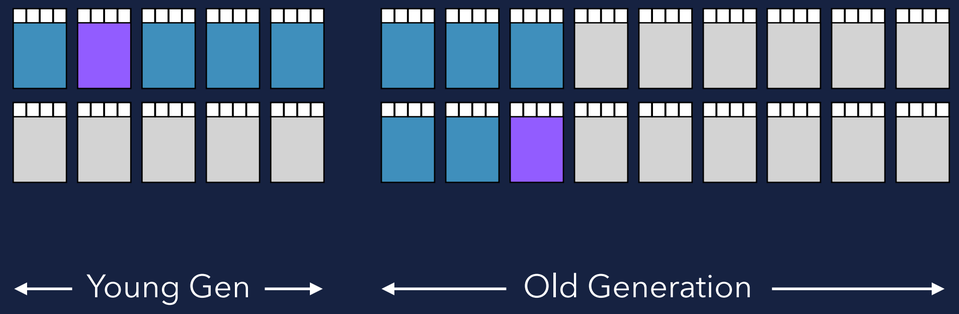
REMEMBERED SET

How to do a minor collection with references from old to young generation...?

REMEMBERED SET

Also known as Card Table





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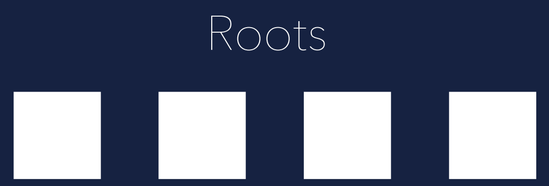

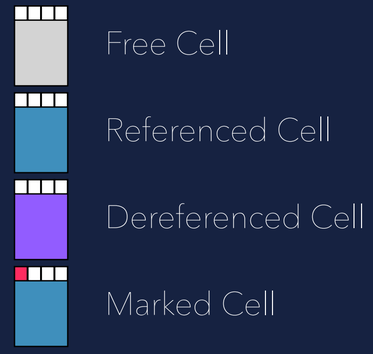

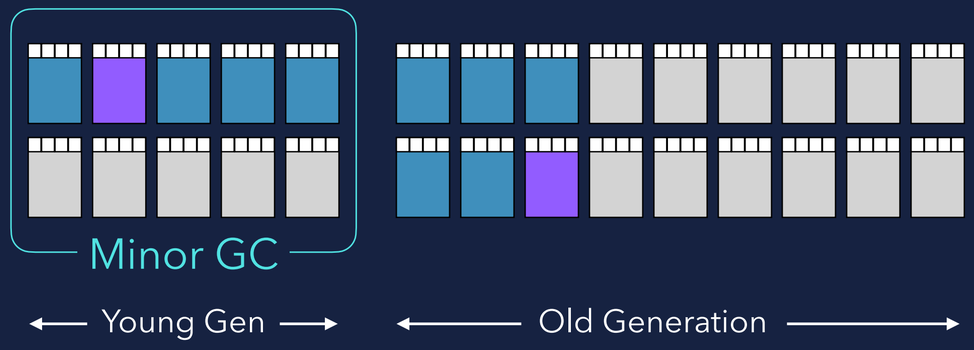

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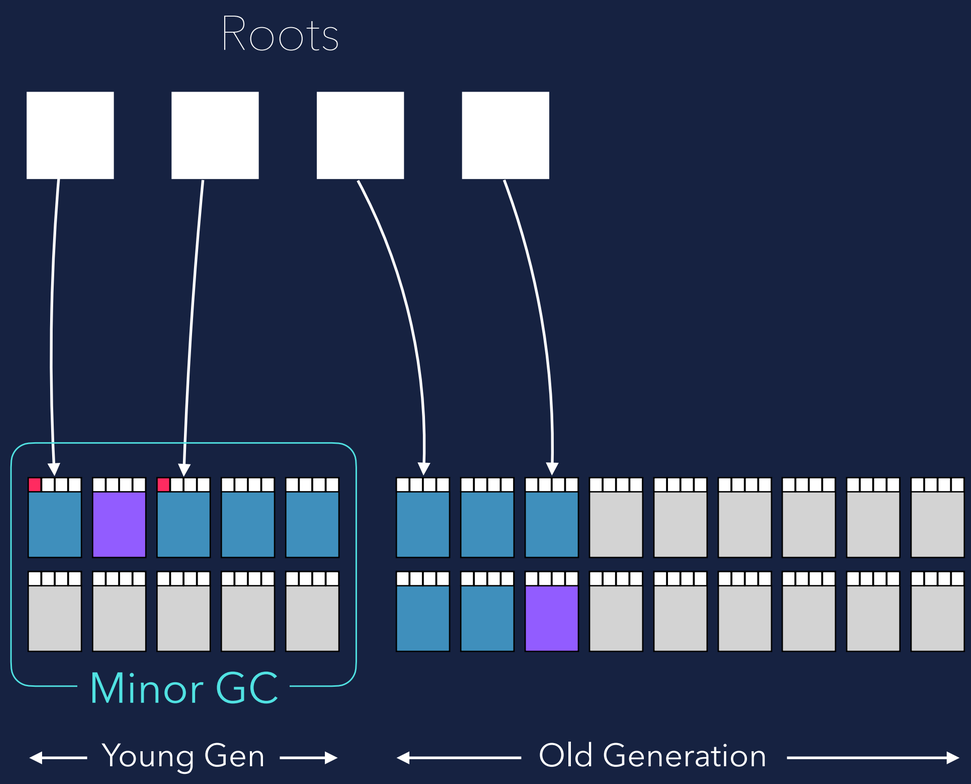

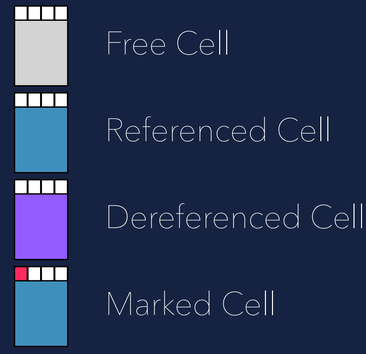

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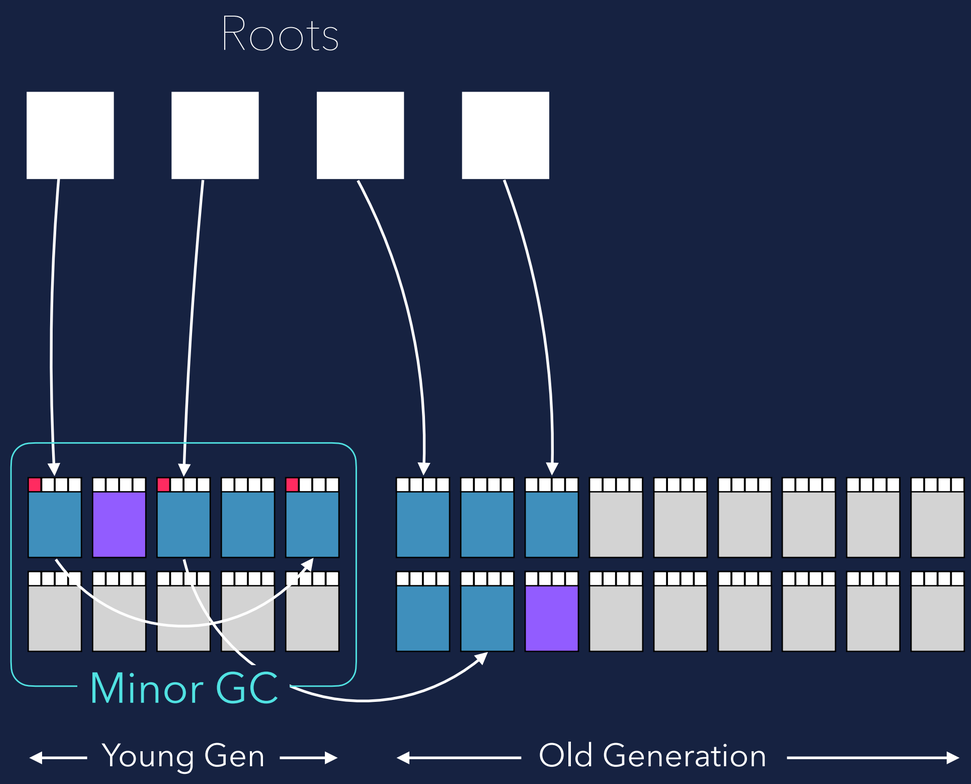

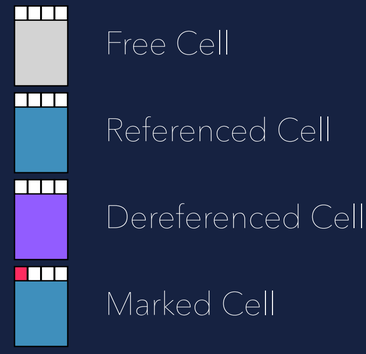

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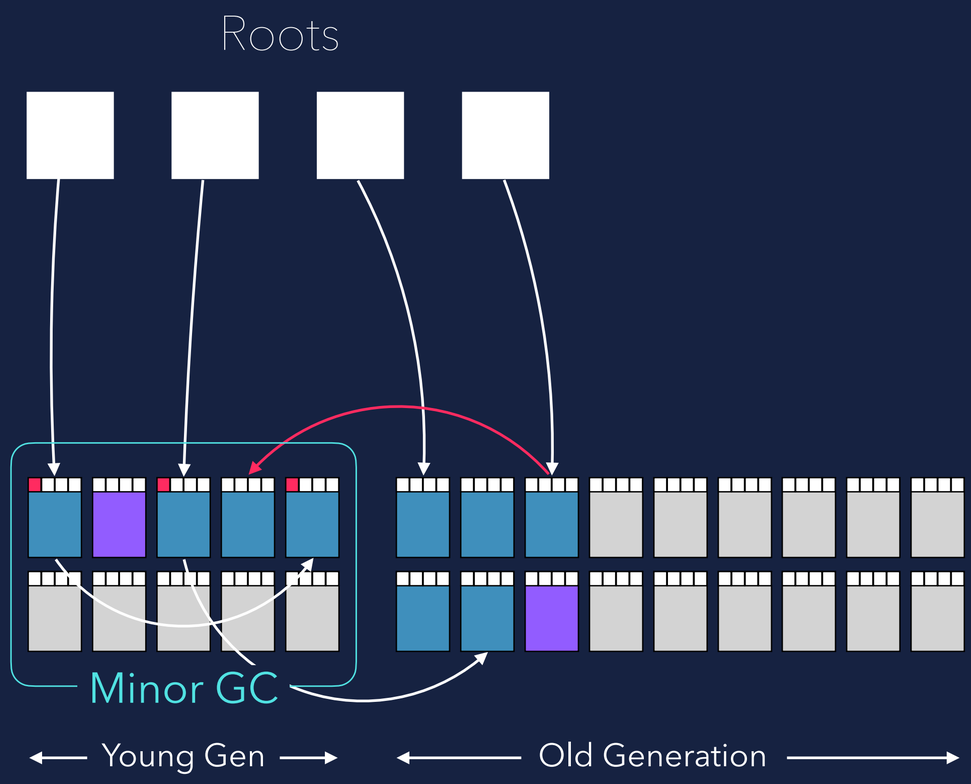

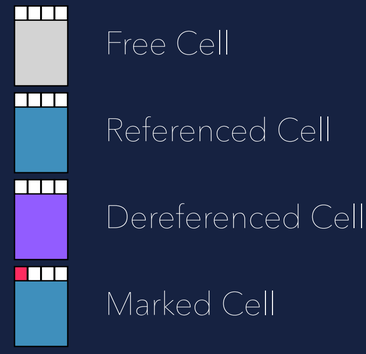

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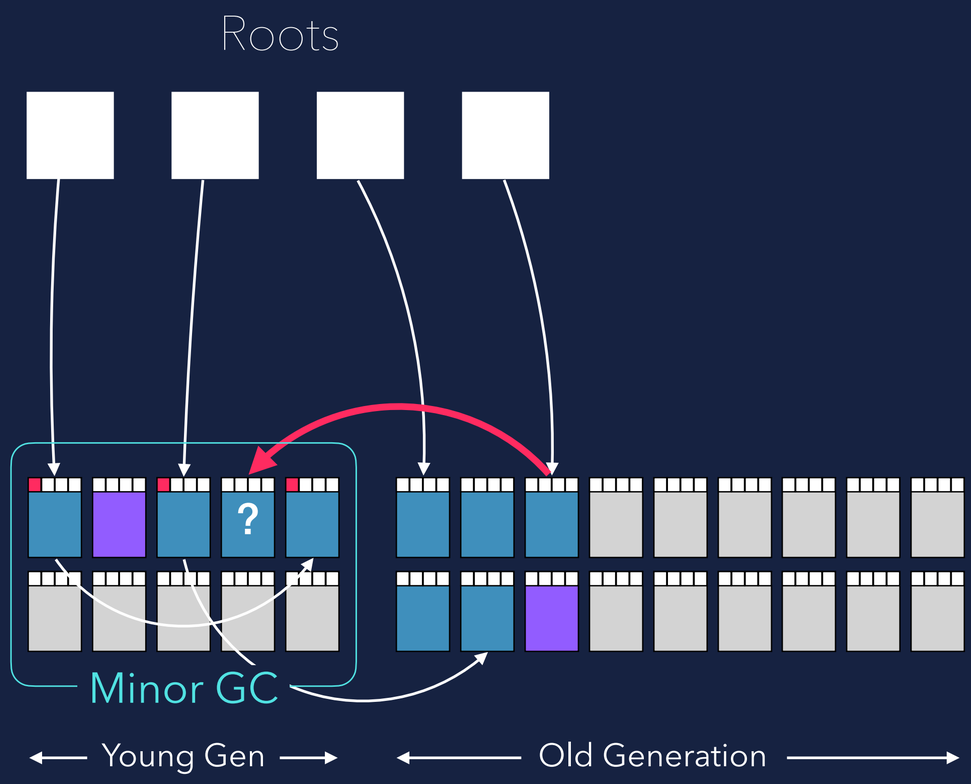

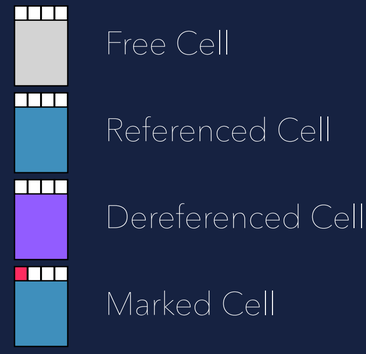

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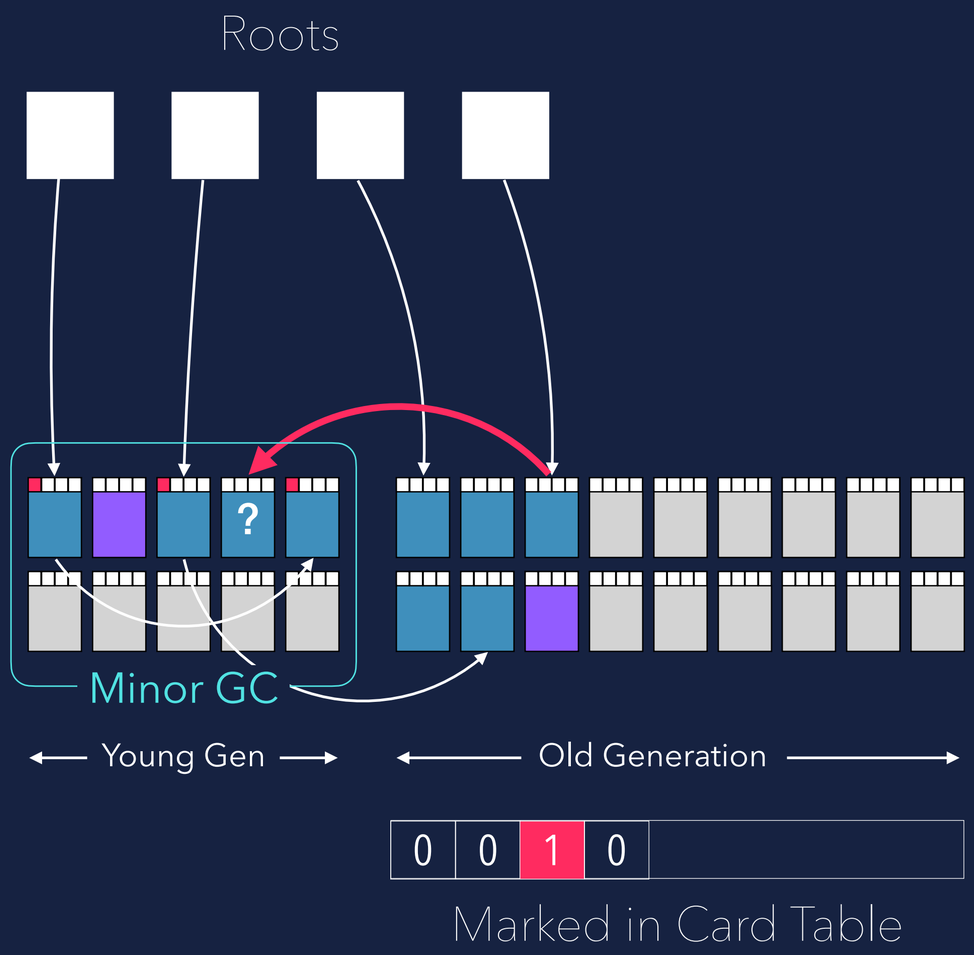

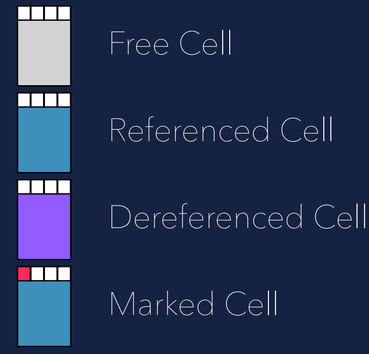

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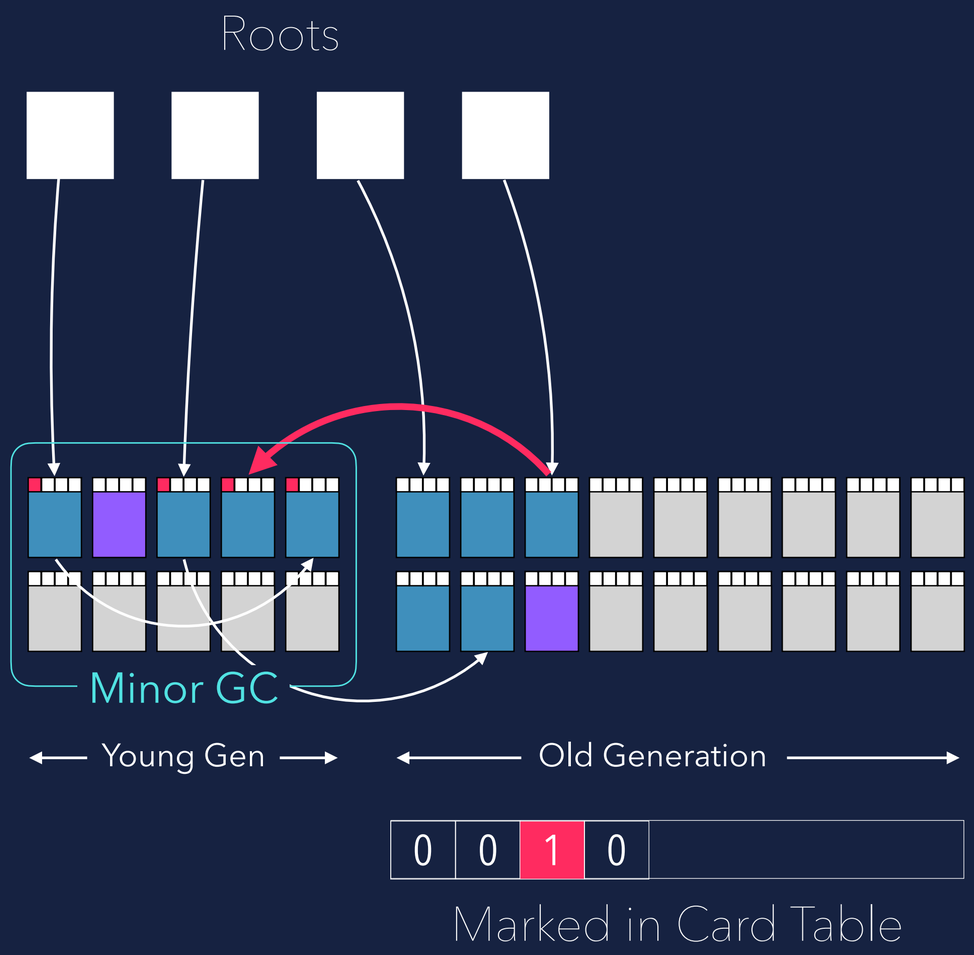
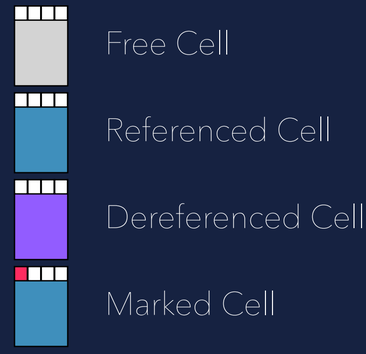




GC looks up Card Table, finds the reference and marks it as live

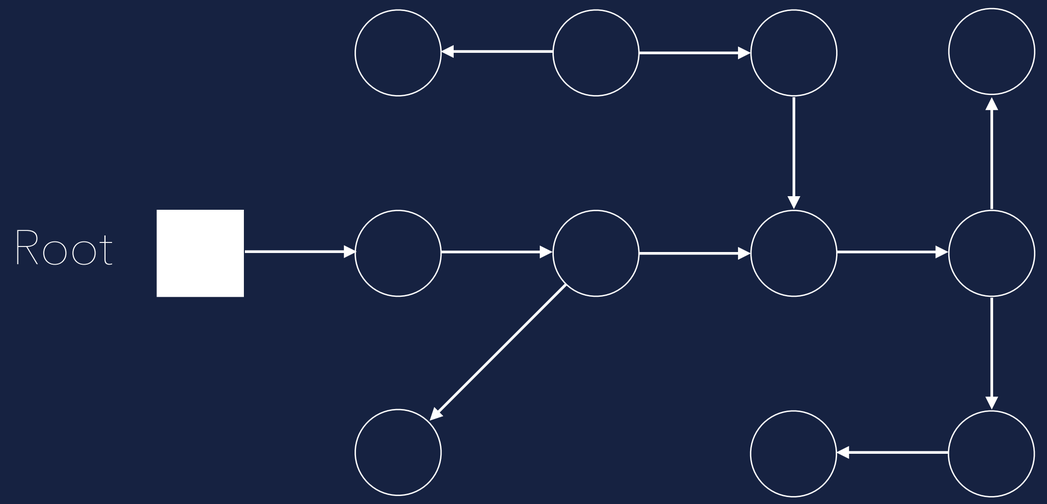
CONCURRENT COLLECTION ?

CONCURRENCY IS HARD...

CONCURRENT MARKING

CONCURRENCY IS HARD...

Concurrent Marking



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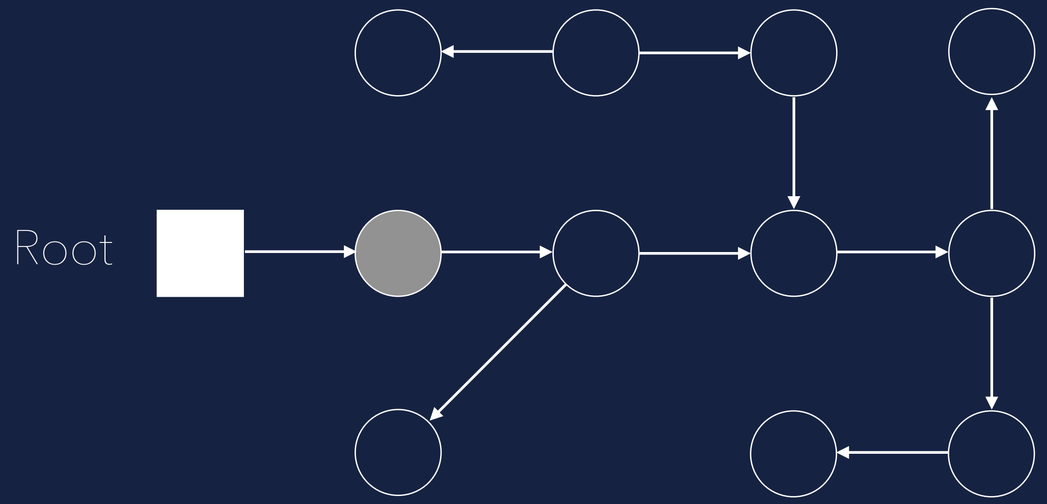

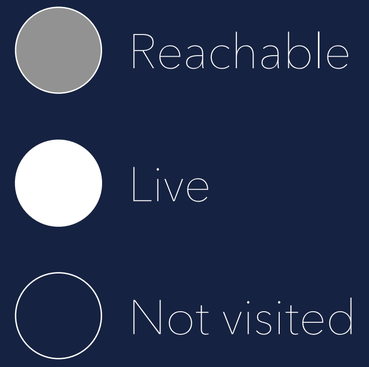

Collector starts marking objects

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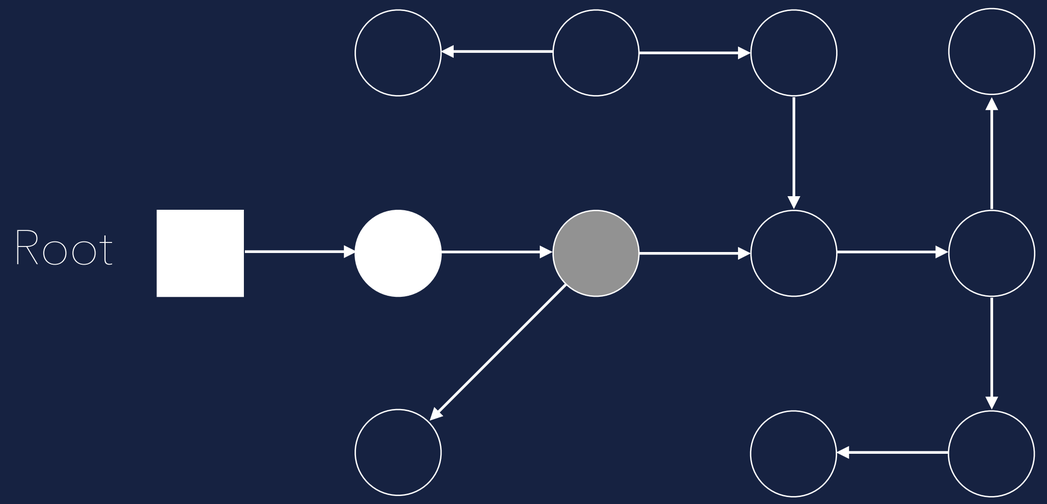

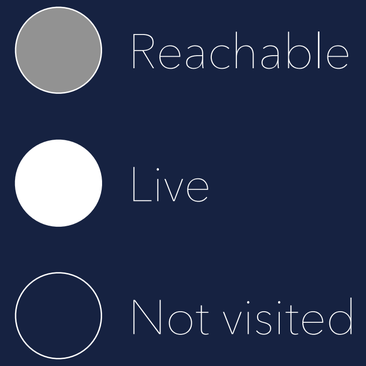

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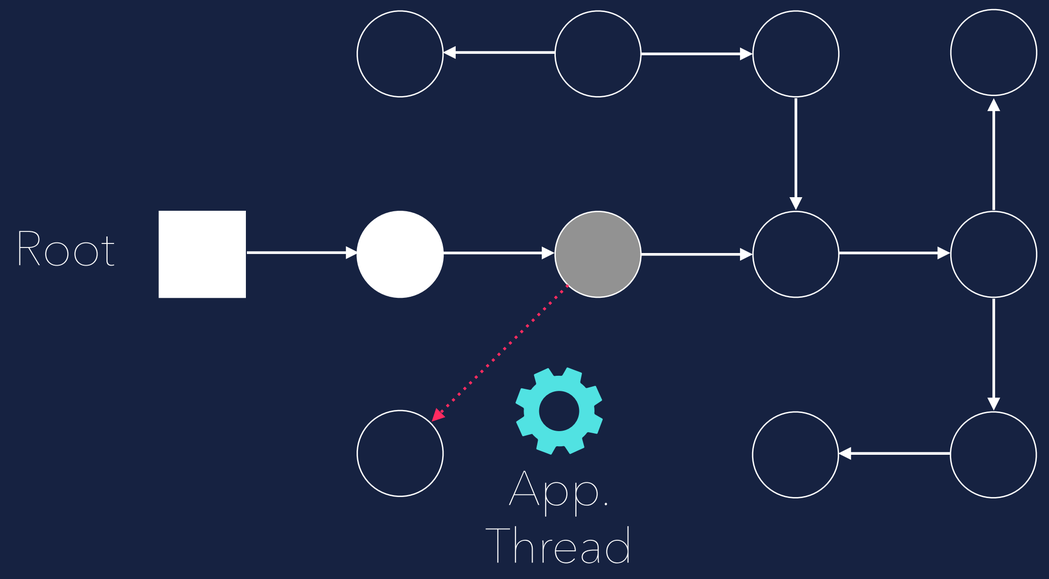

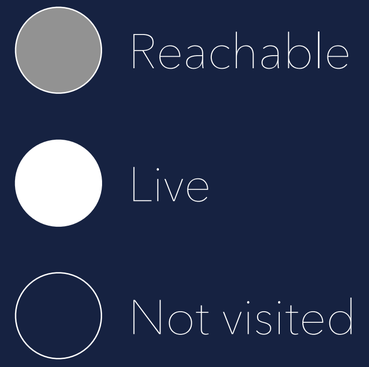

Mutator removes reference and creates a new one from an already visited cell !

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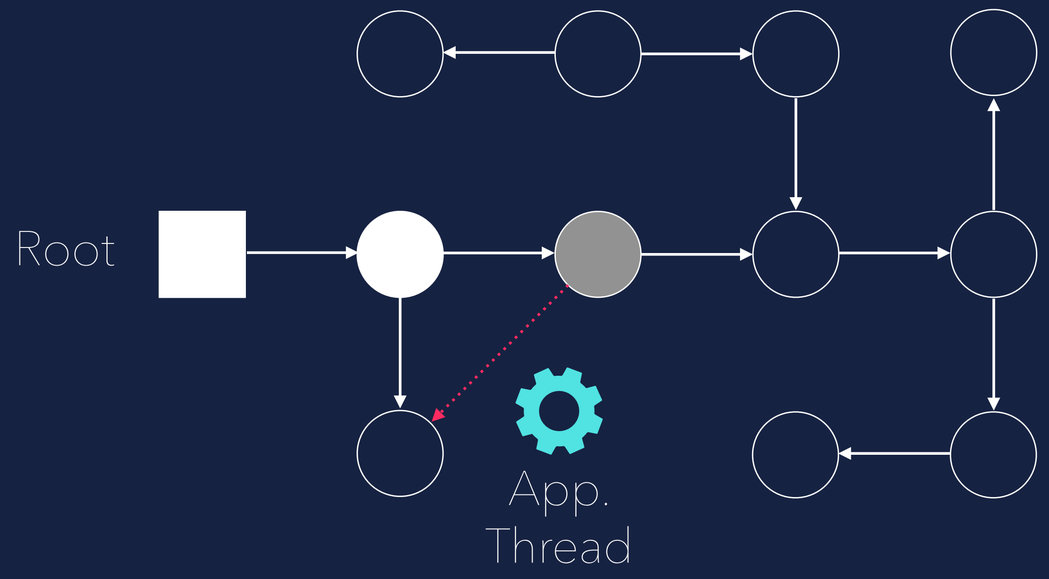

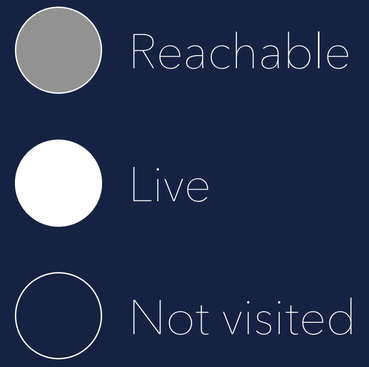

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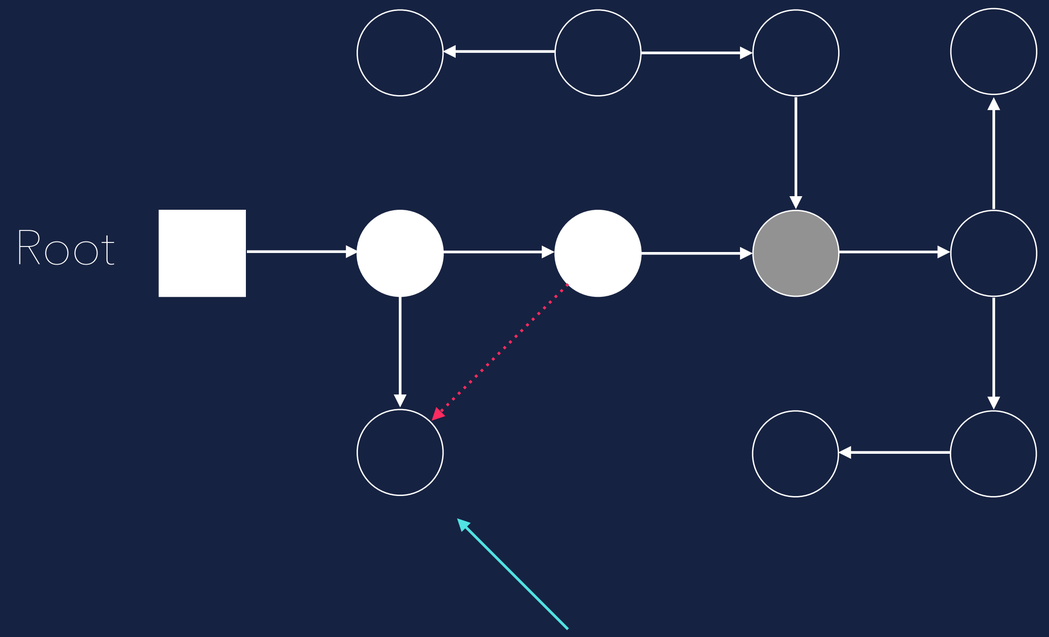
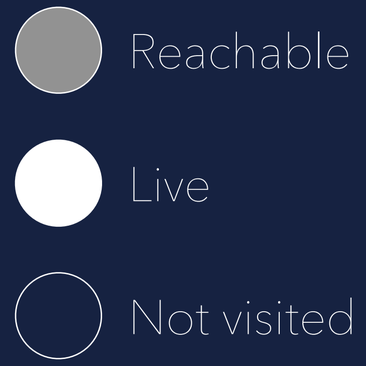
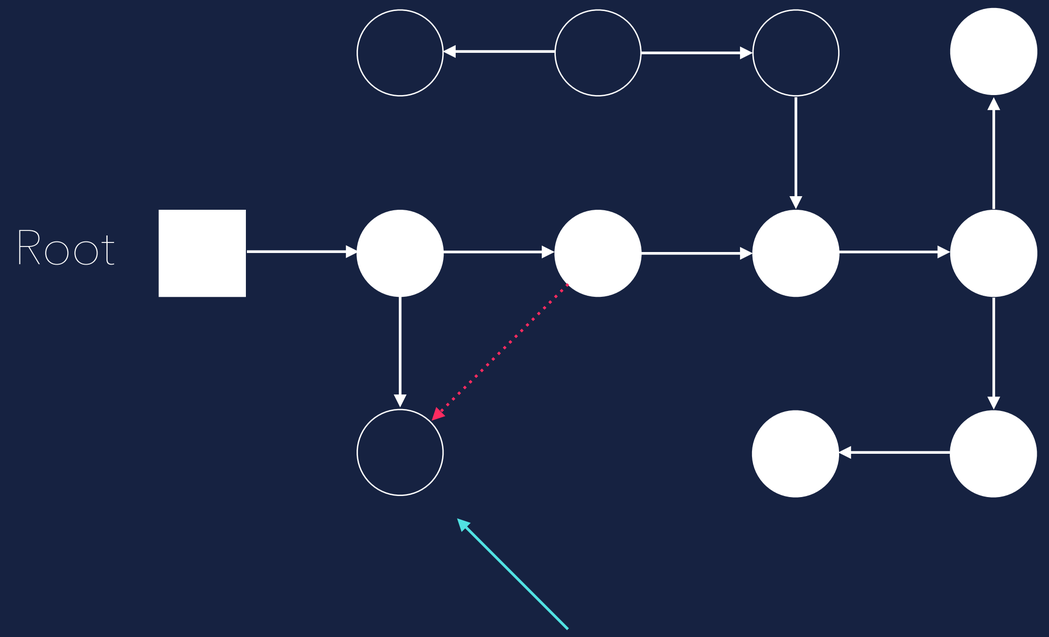


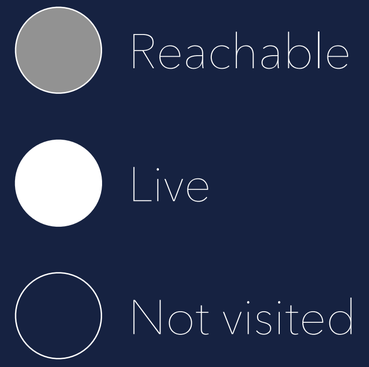


Won't be detected by the Garbage Collector !

CONCURRENCY IS HARD...

Concurrent Marking





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BARRIERS TO THE RESCUE

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Read / Write Barriers

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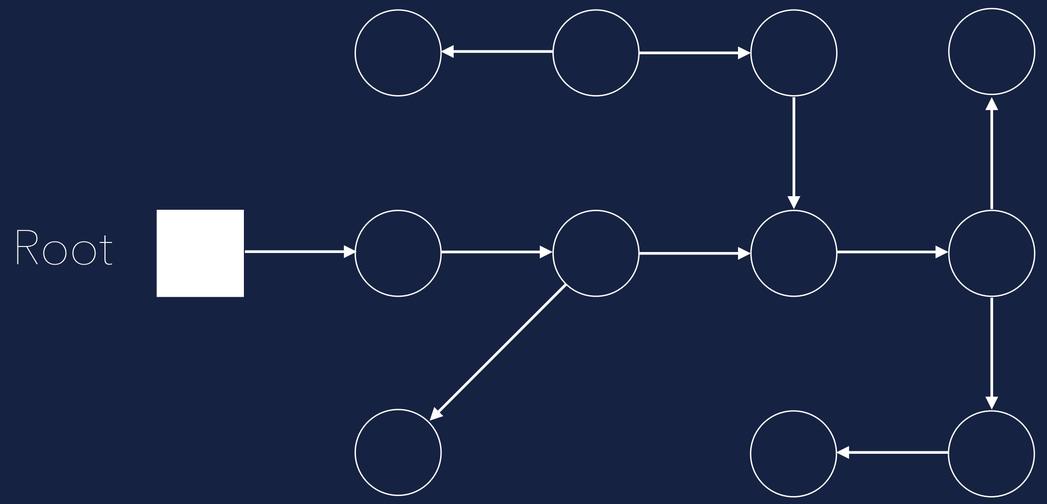
  (references from old generation to young generation, the so called Rembered Set)
- Used to synchronize action between mutator and collector
  (allocation concurrent to collection)
- Read Barriers are usually more expensive
  (reads 75% to writes 25% -> Read Barriers must be very efficient)

CONCURRENCY IS HARD...

Concurrent Marking using Write Barriers



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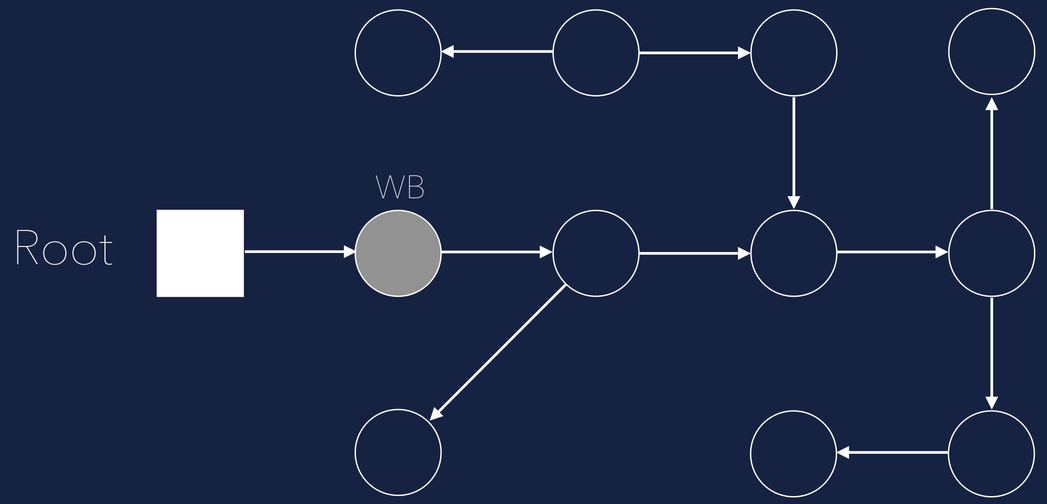

Collector starts marking objects

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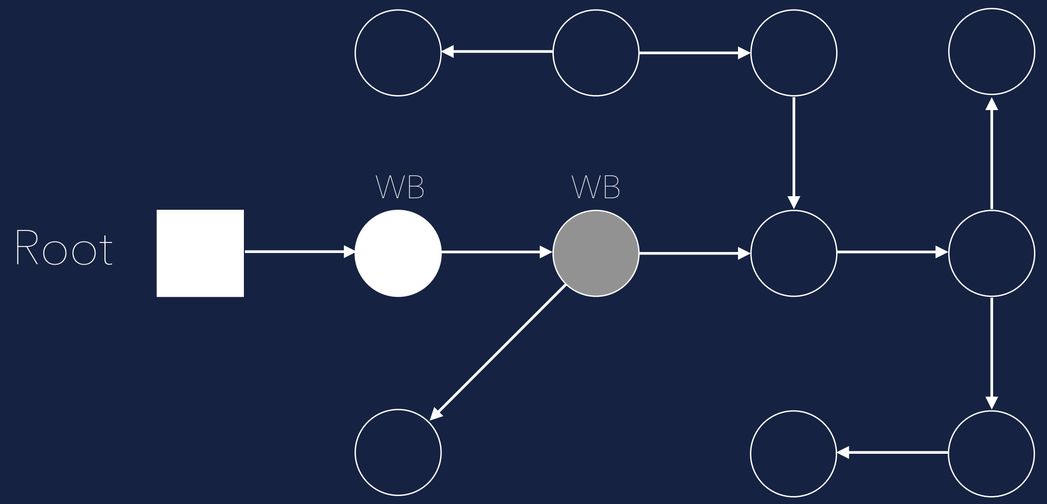

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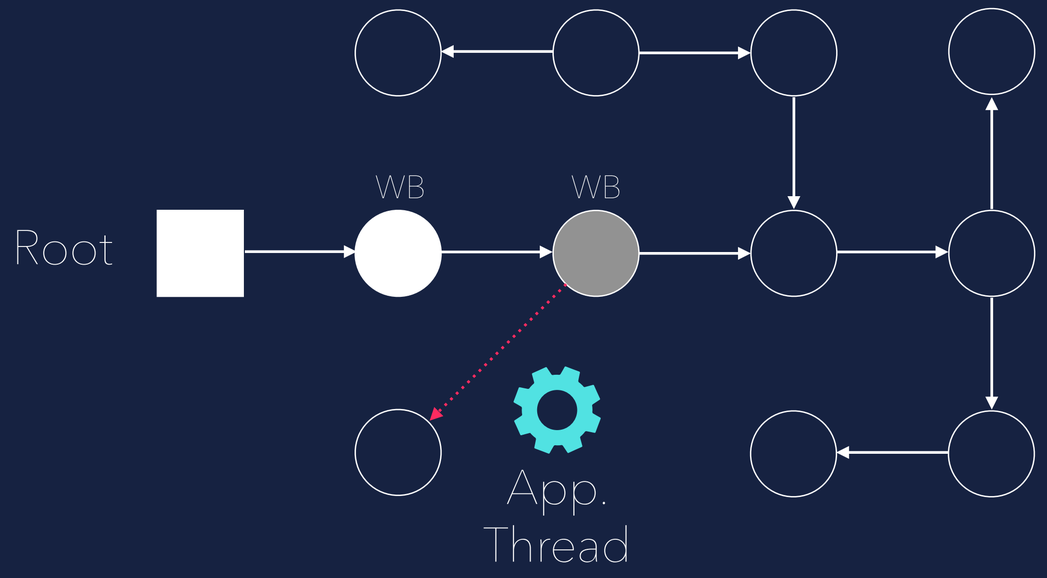

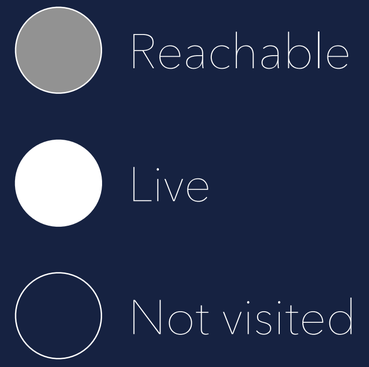

Mutator hits write barrier and removes reference and adds a new one

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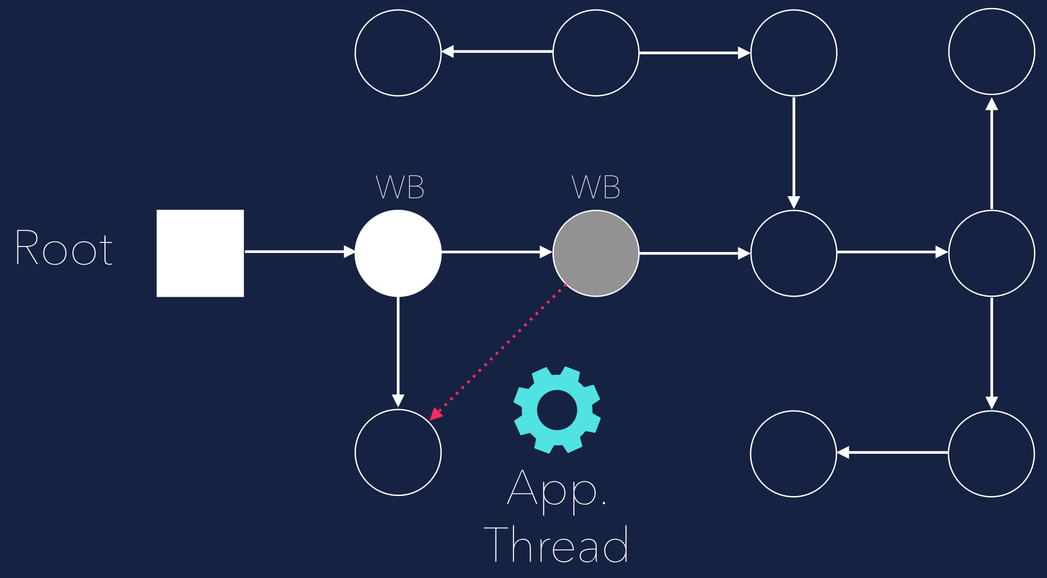

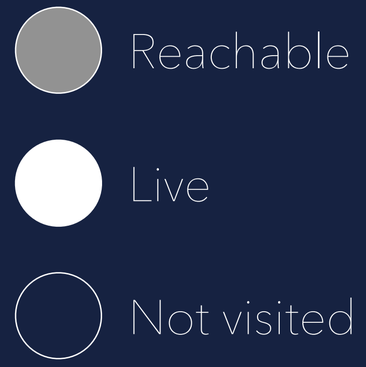

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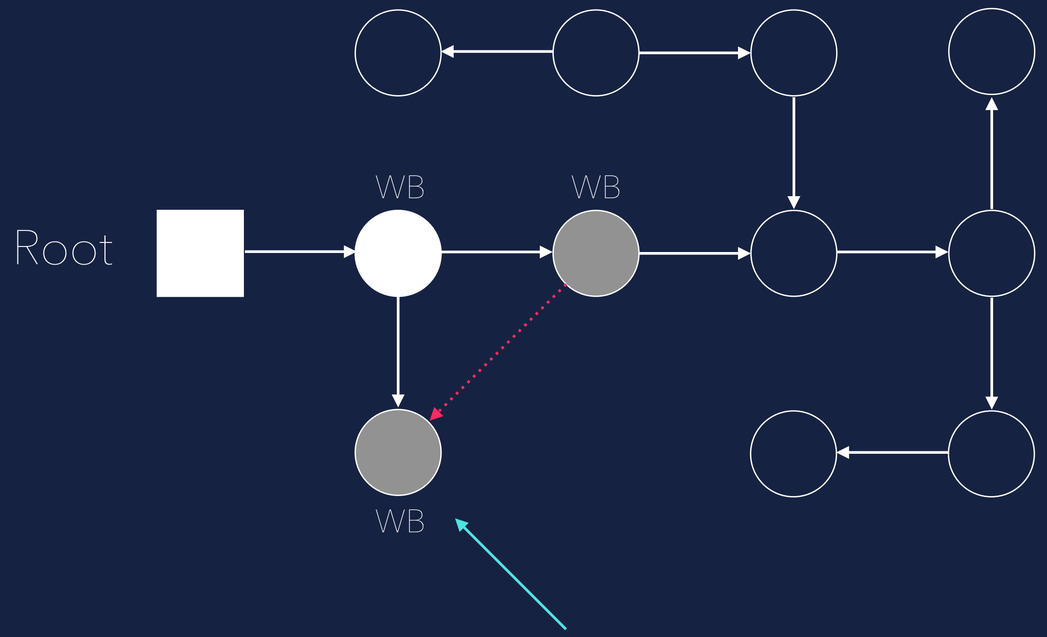
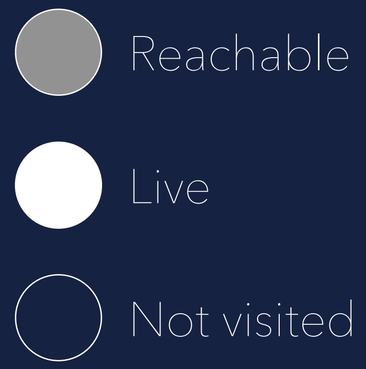
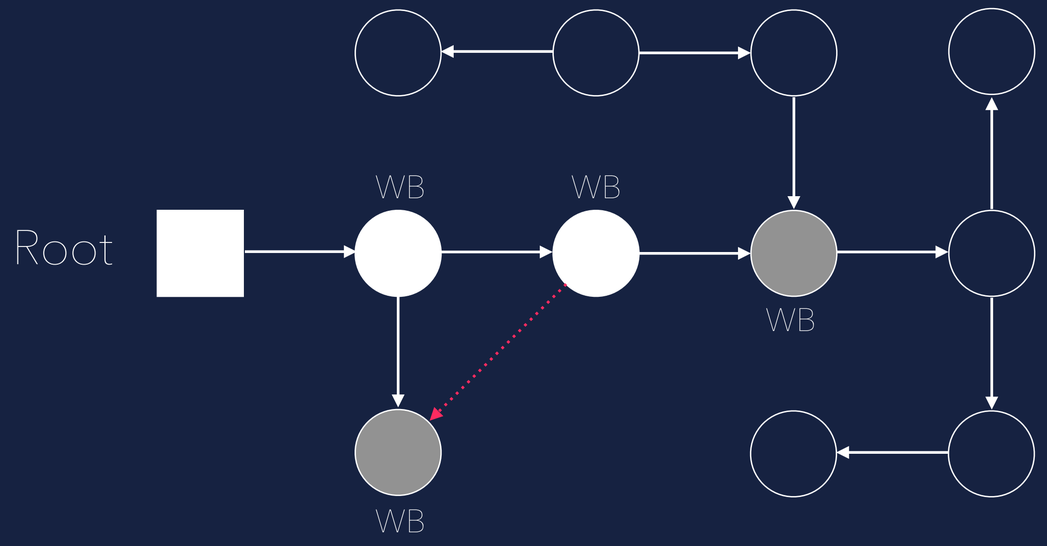


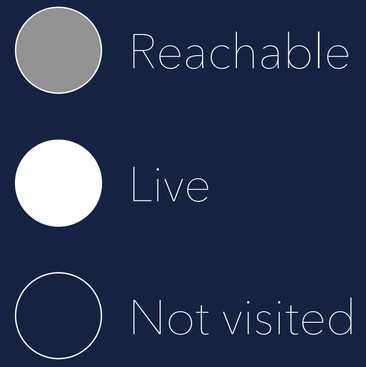


Removed references will be marked as reachable by Write Barrier

CONCURRENCY IS HARD...

Concurrent Marking using Write Barriers





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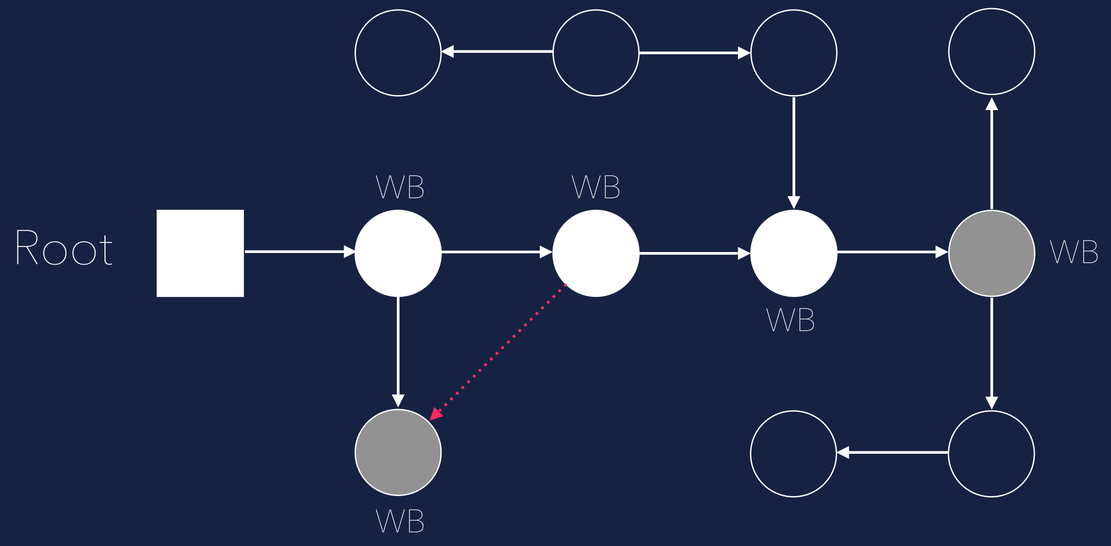

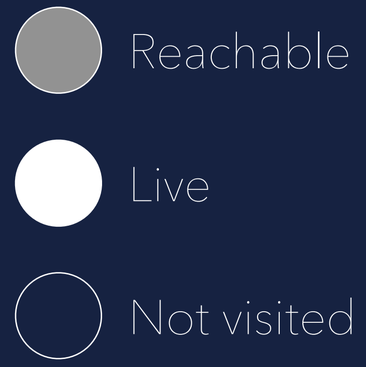

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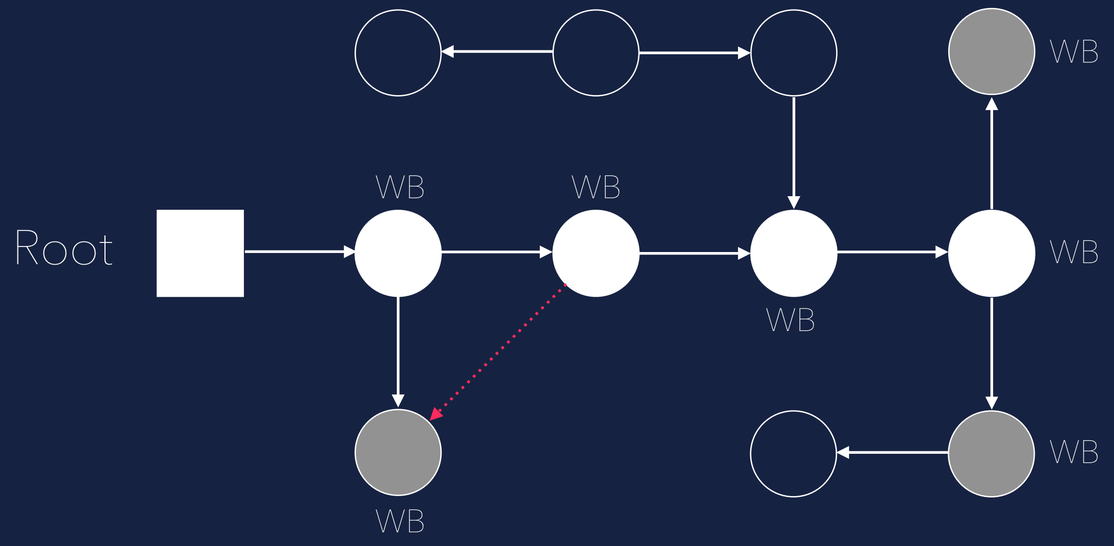

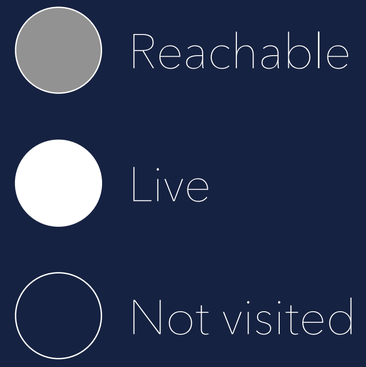

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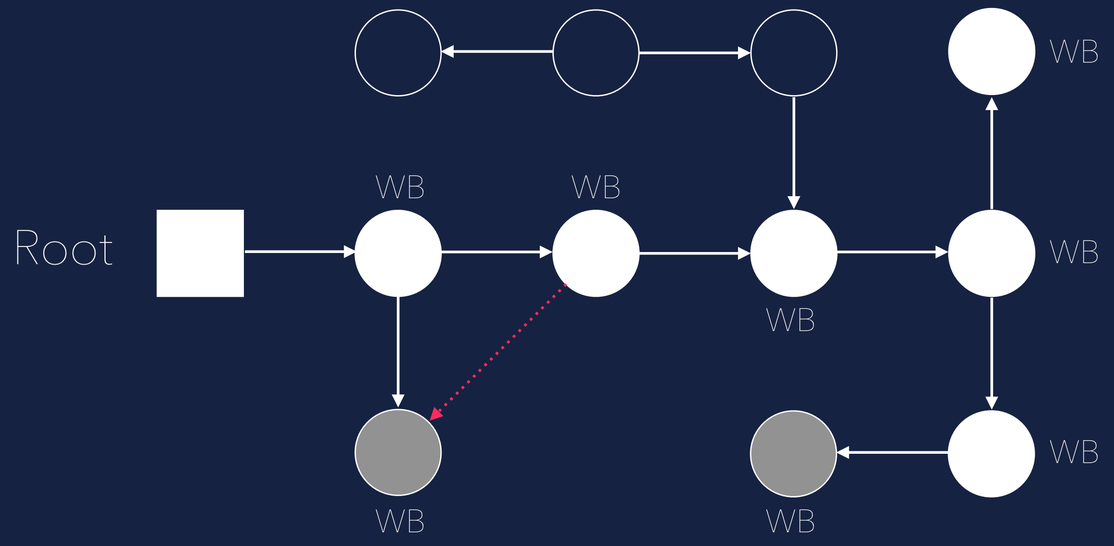

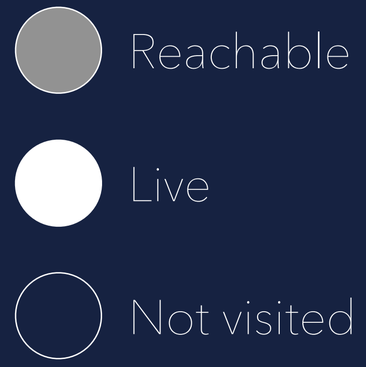

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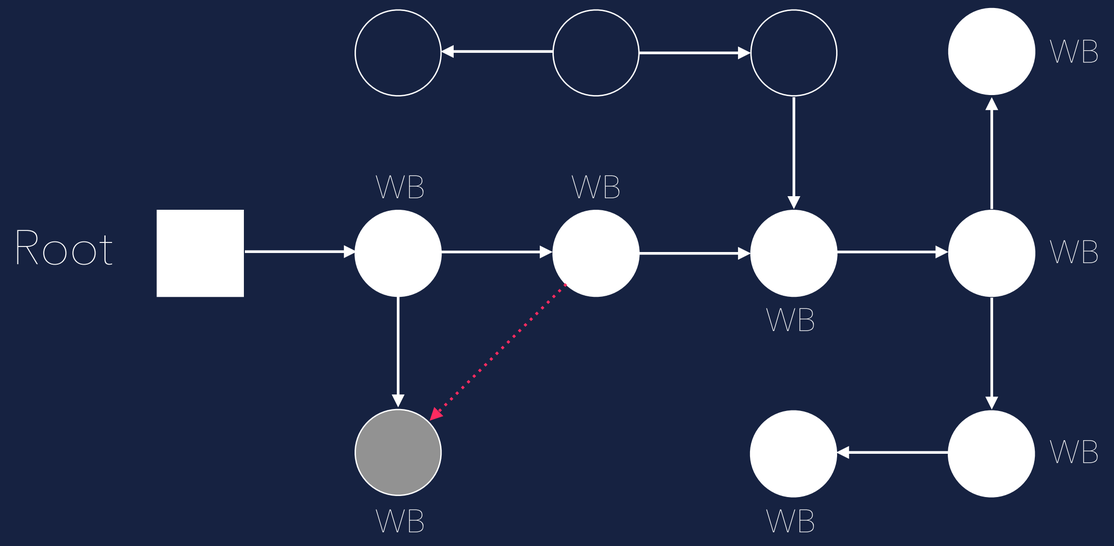

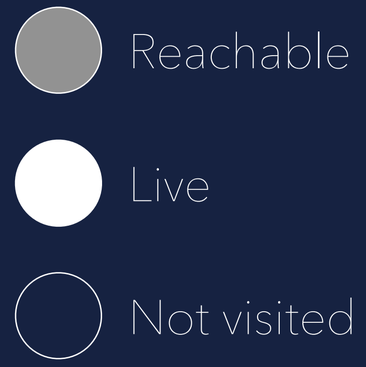

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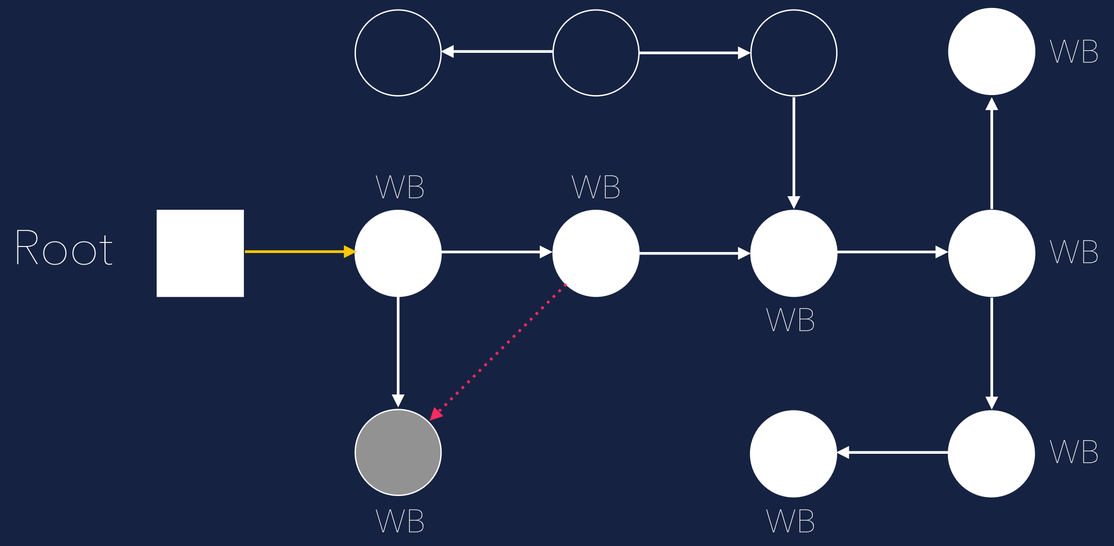

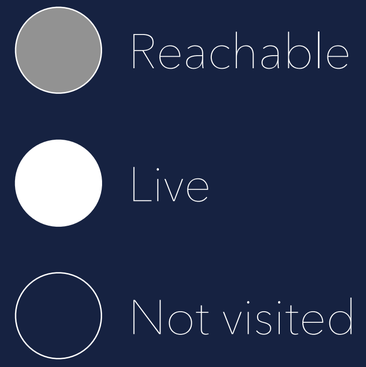

In the Re-Marking phase, in between marked references will be marked as live

CONCURRENCY IS HARD...

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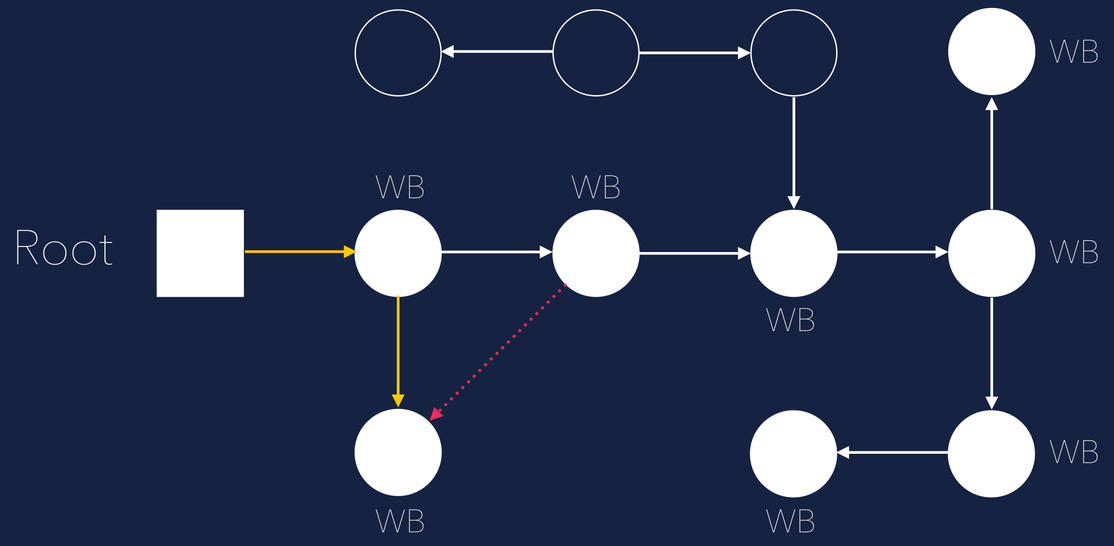

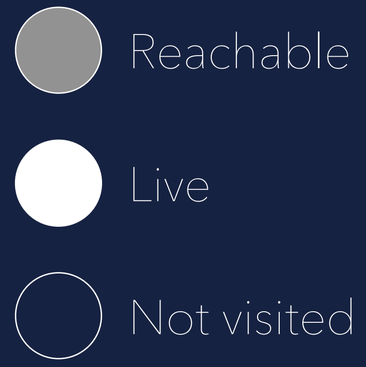

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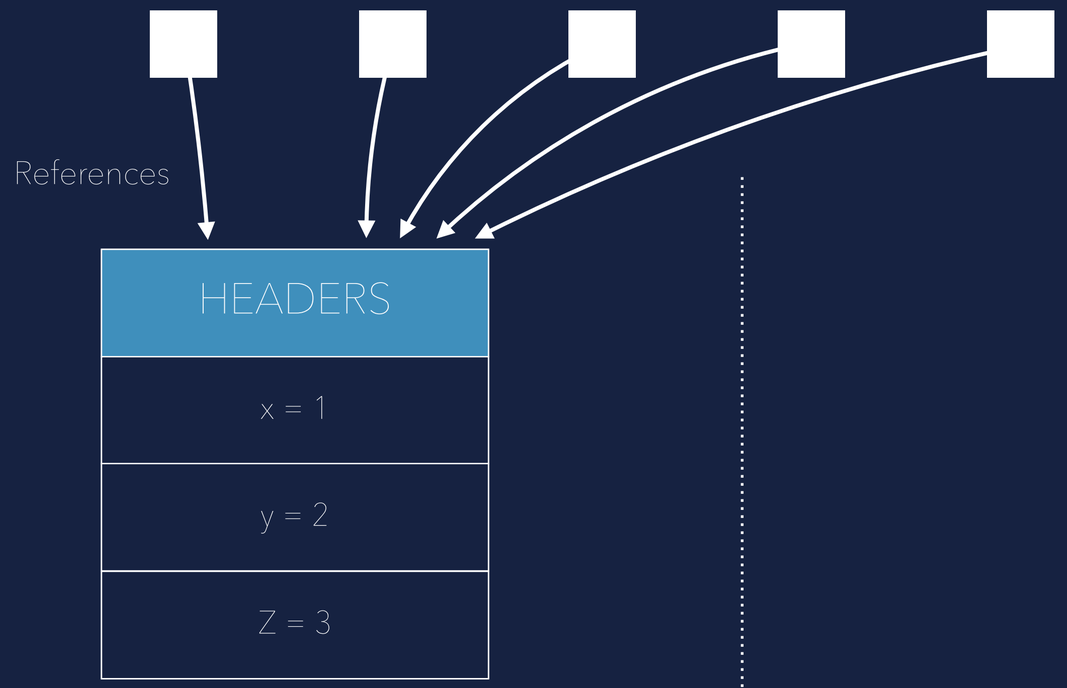
CONCURRENT COPYING

CONCURRENCY IS HARD...

Stop the world copying



FROM Space

TO Space

CONCURRENCY IS HARD...

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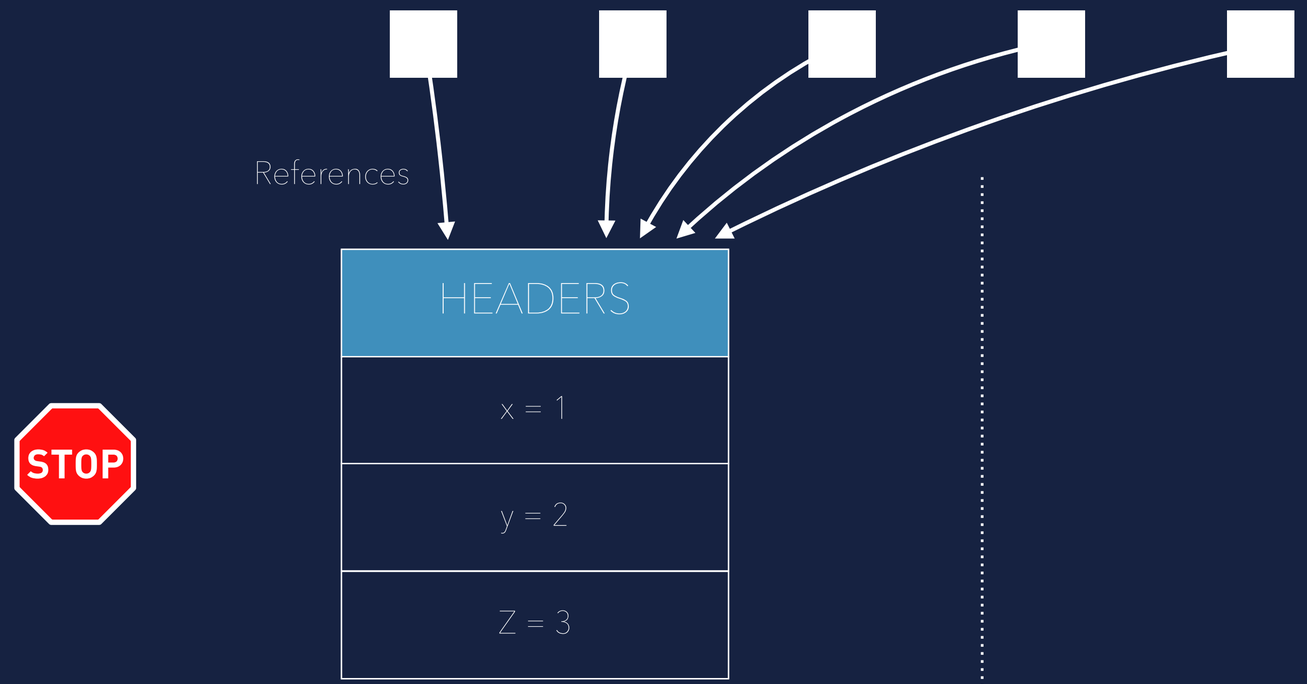

Stop the World
(the Mutator)

FROM Space

TO Space

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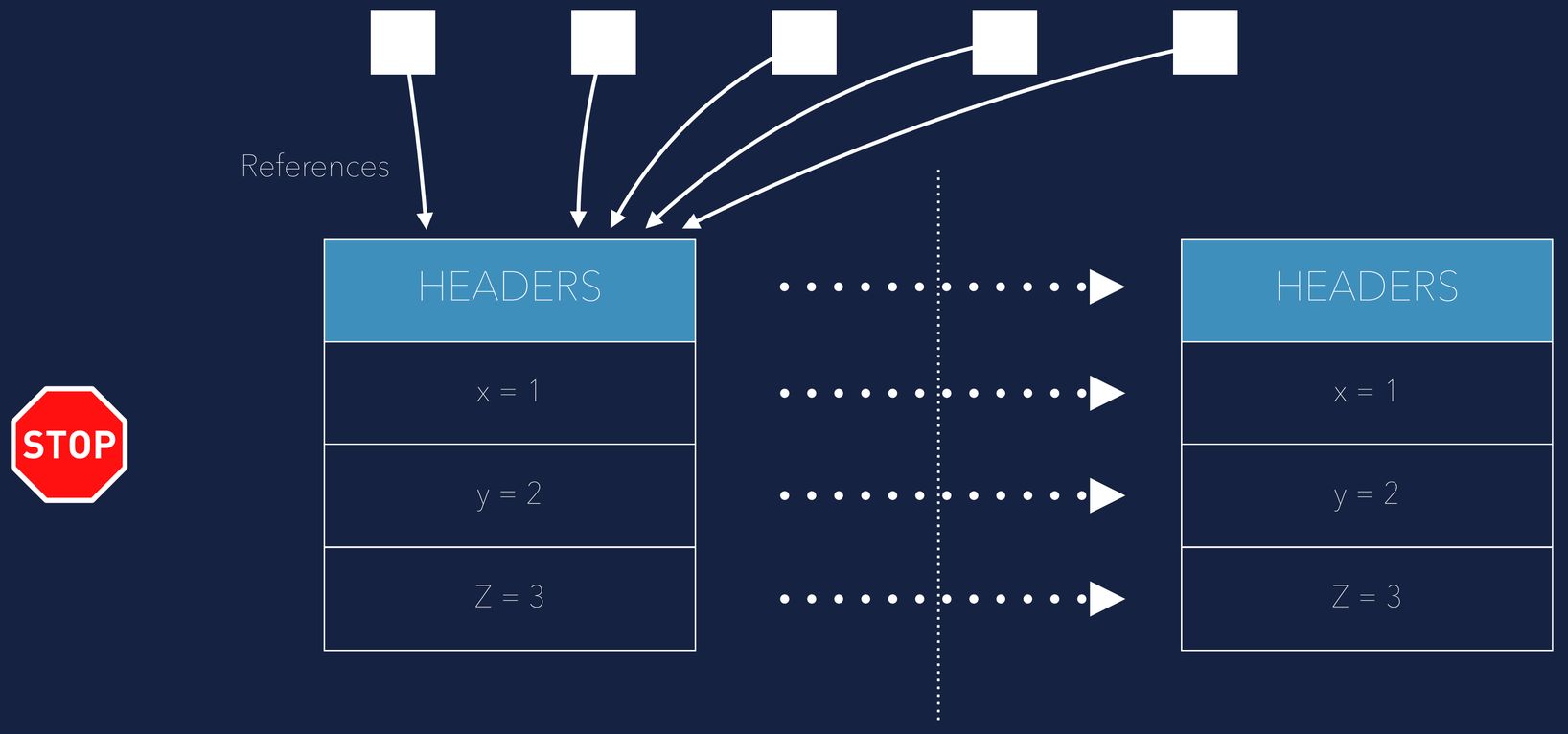
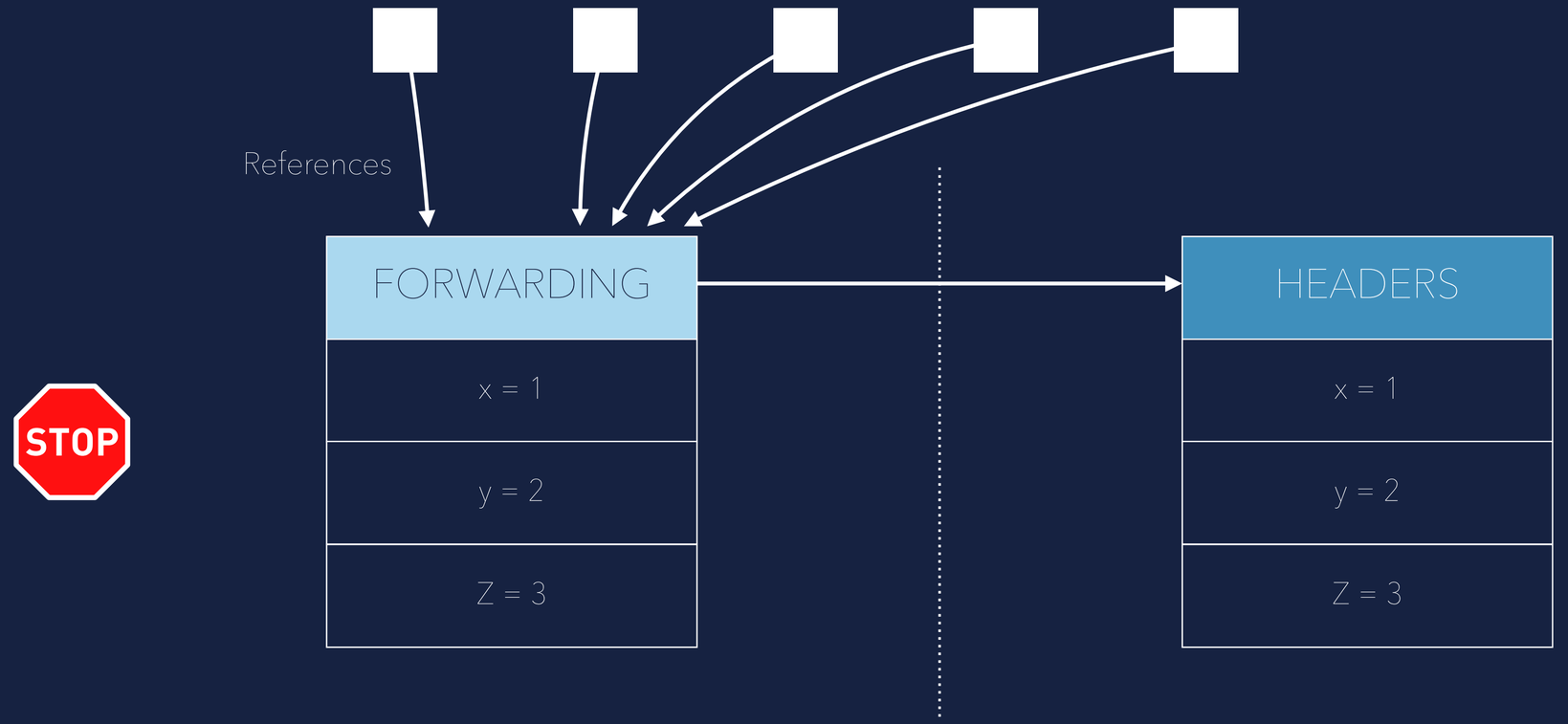


Copy the Object
(Create forwarding pointer)

CONCURRENCY IS HARD...

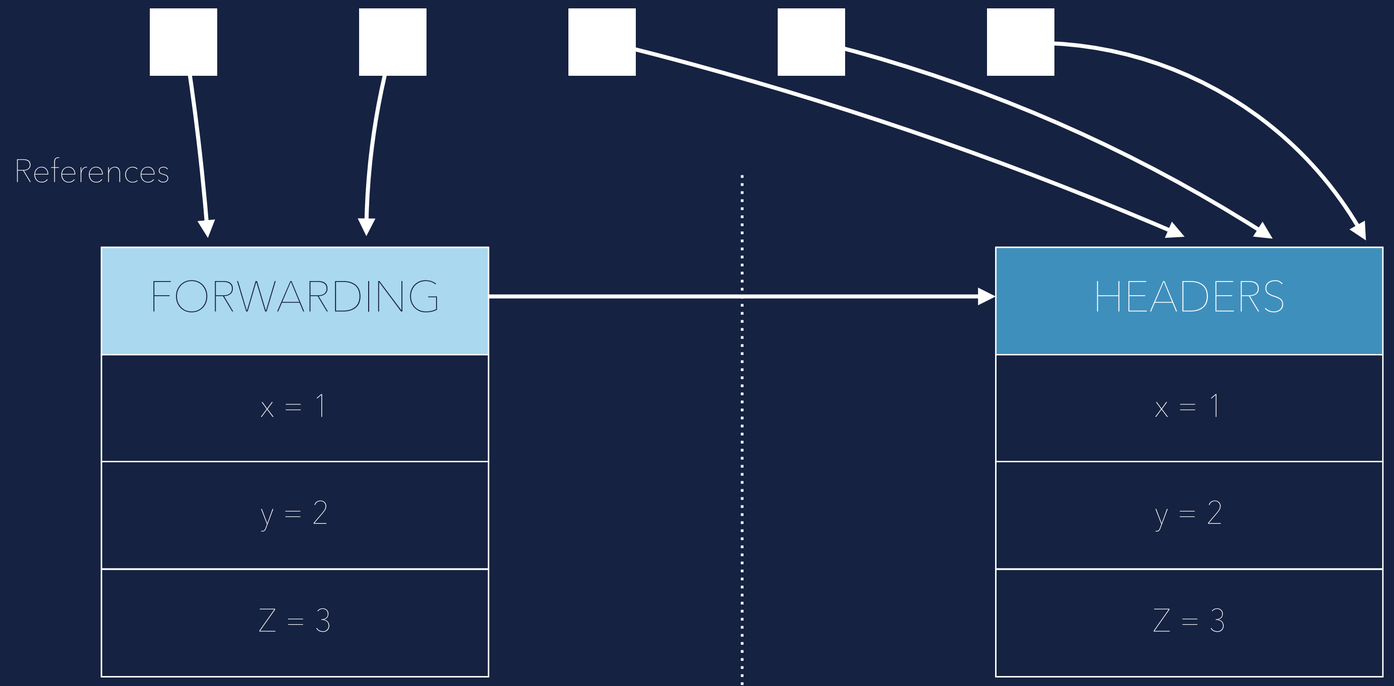
Stop the world copying



Update all references
(Save the pointer that fowards the copy)

CONCURRENCY IS HARD...

Stop the world copying

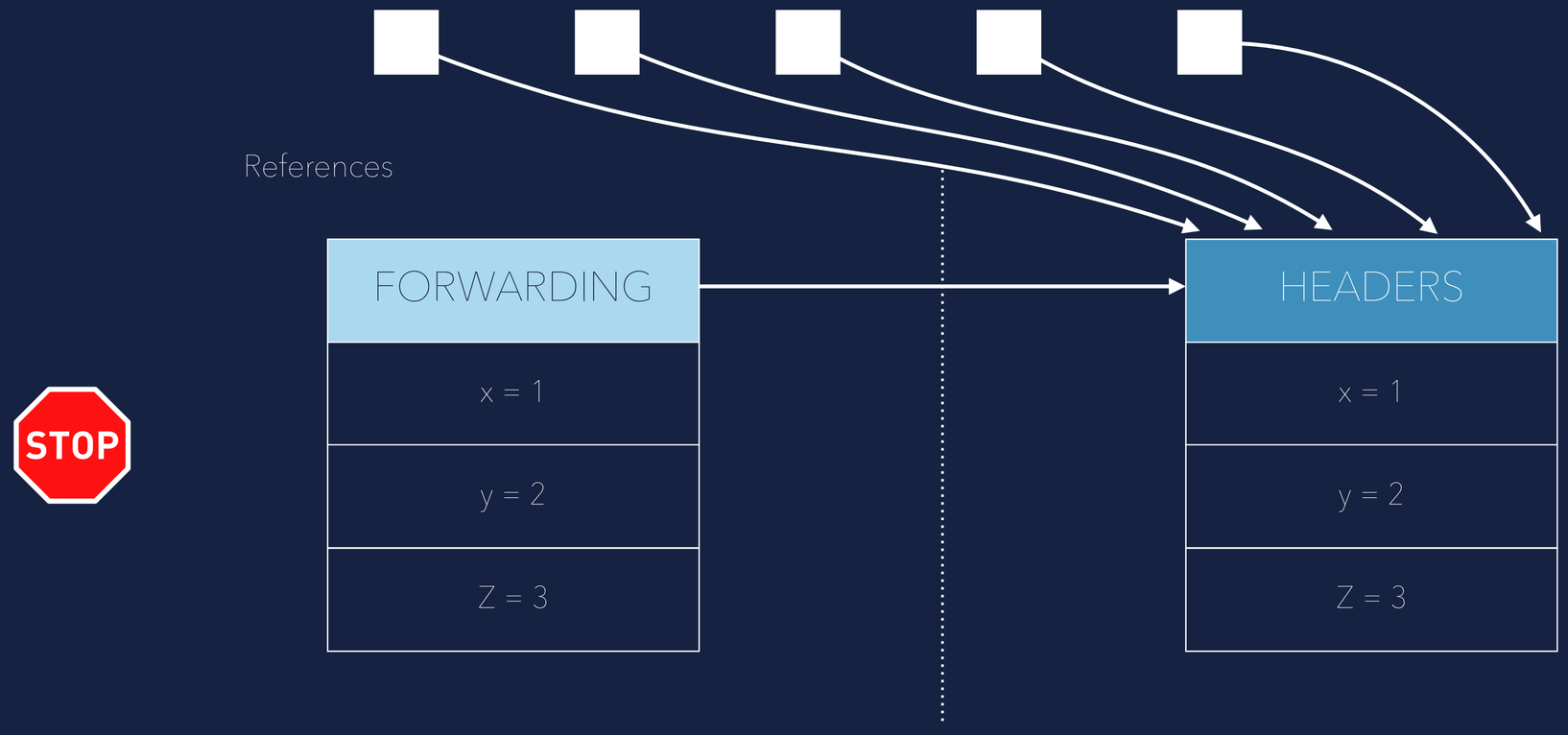


Update all references

(Walk the heap and replace all references with forwarding pointer to new location)

CONCURRENCY IS HARD...

Stop the world copying



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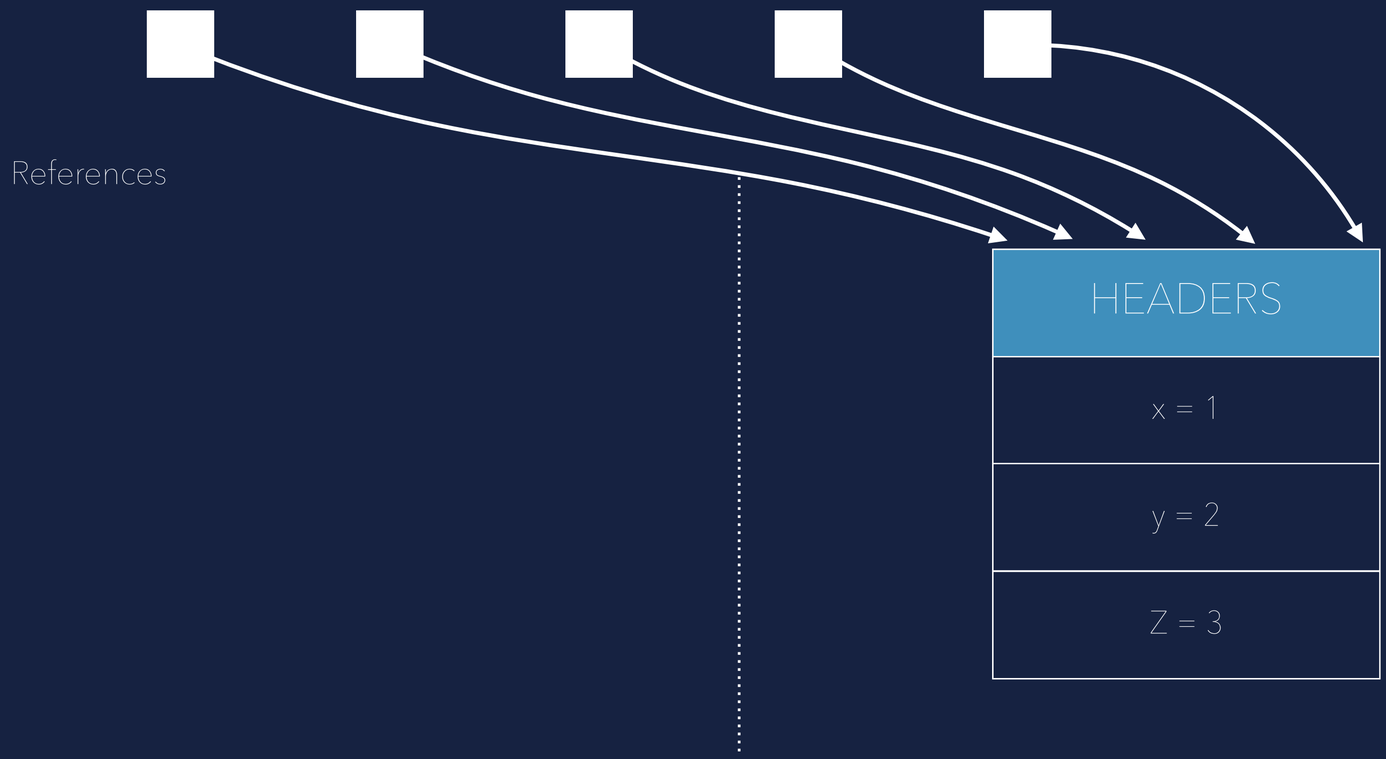
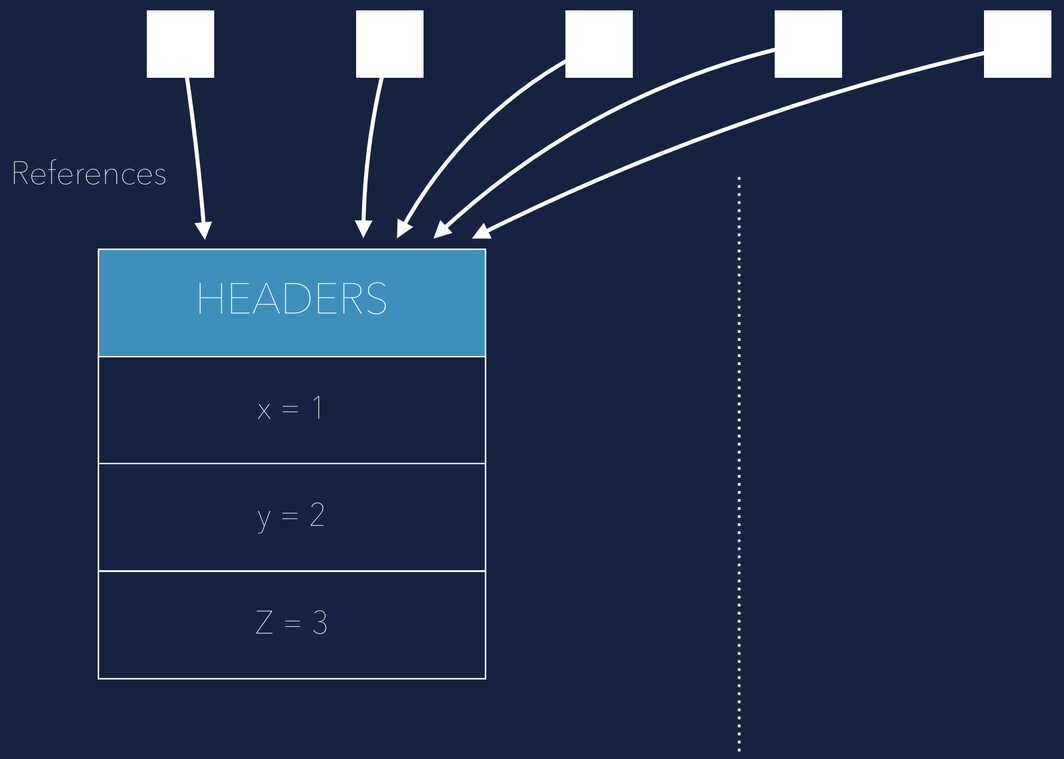


Remove old objects and continue running the Mutator

CONCURRENCY IS HARD...

Concurrent copying



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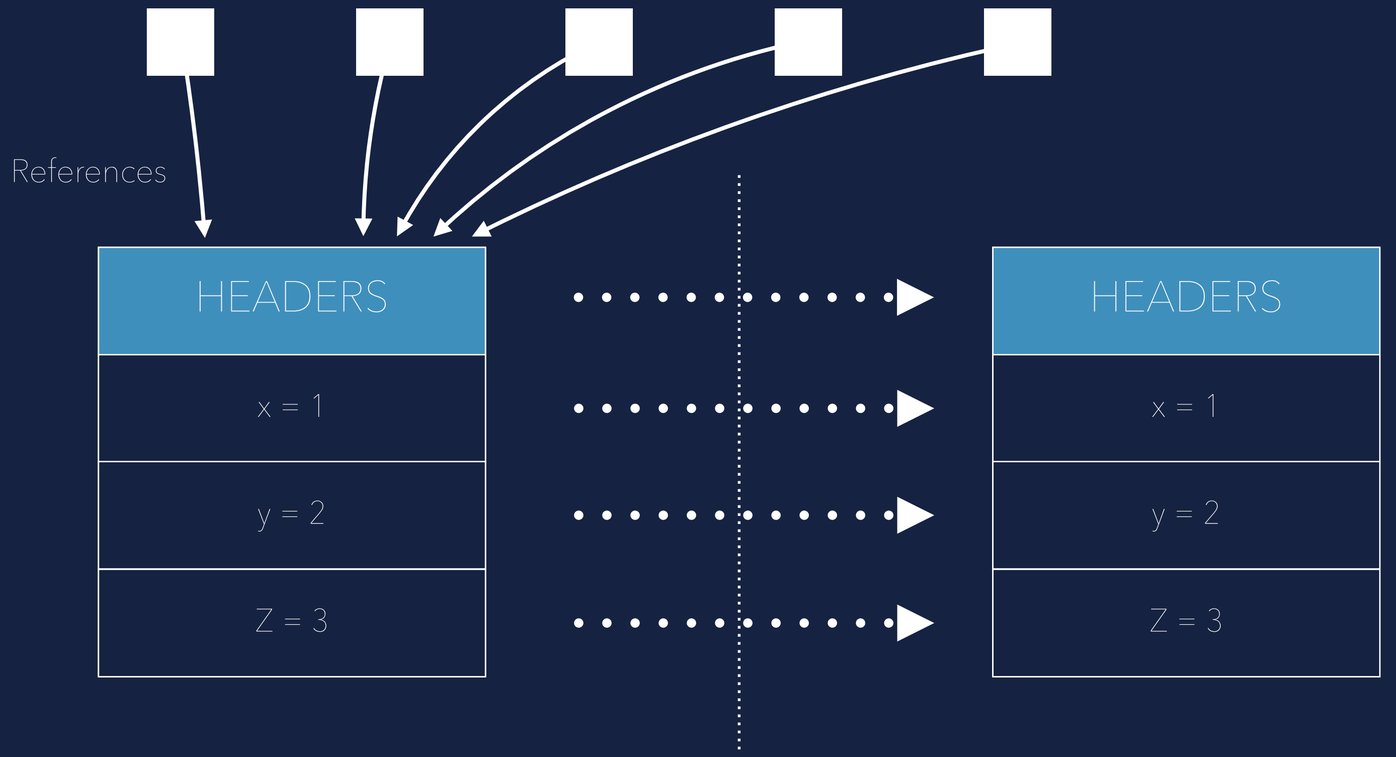
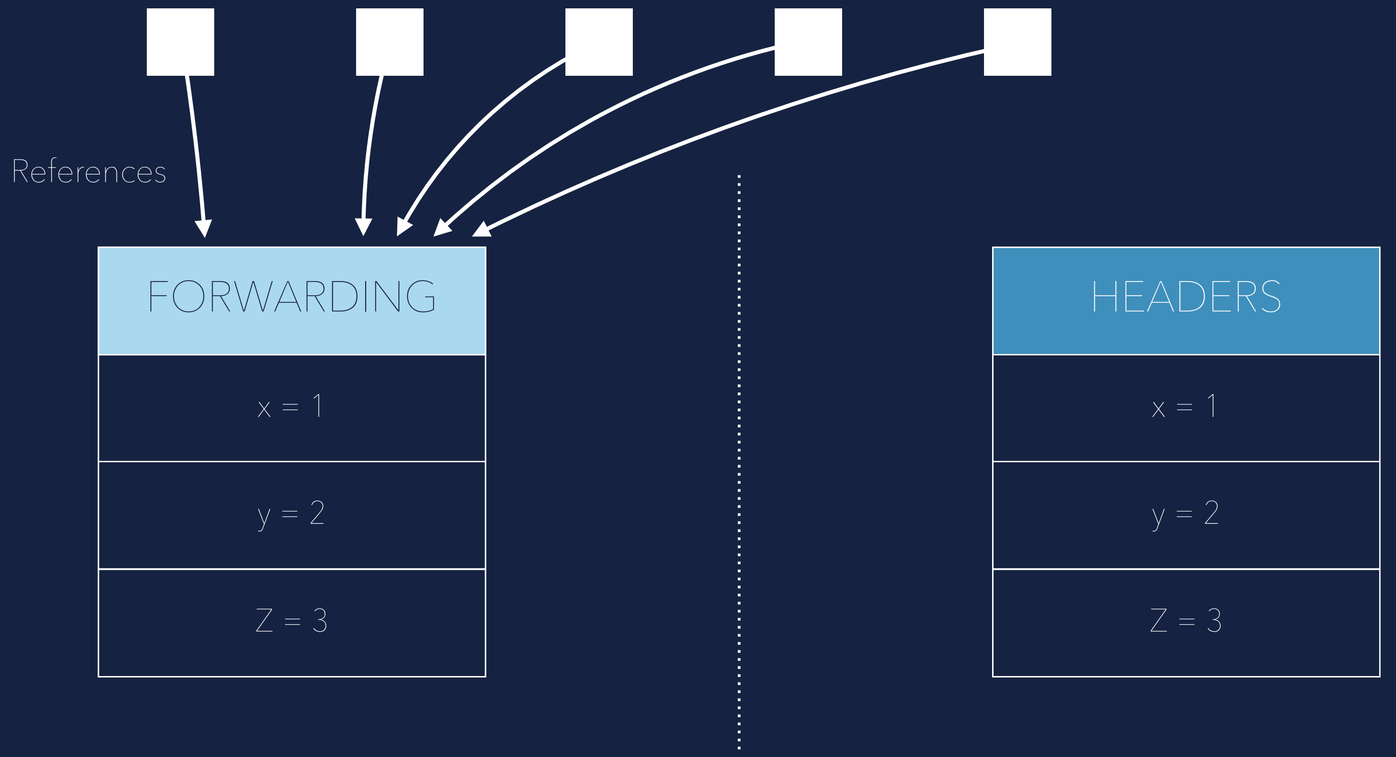


While copying
the Object...

CONCURRENCY IS HARD...

Concurrent copying



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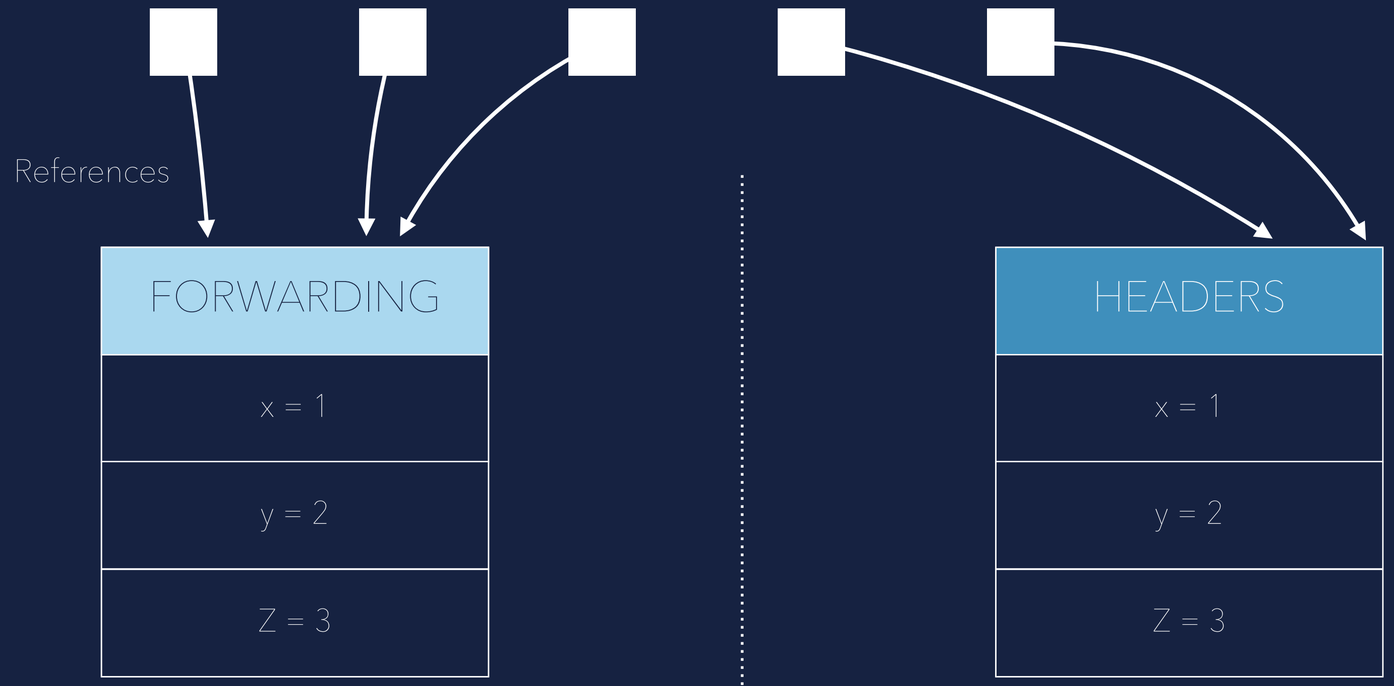
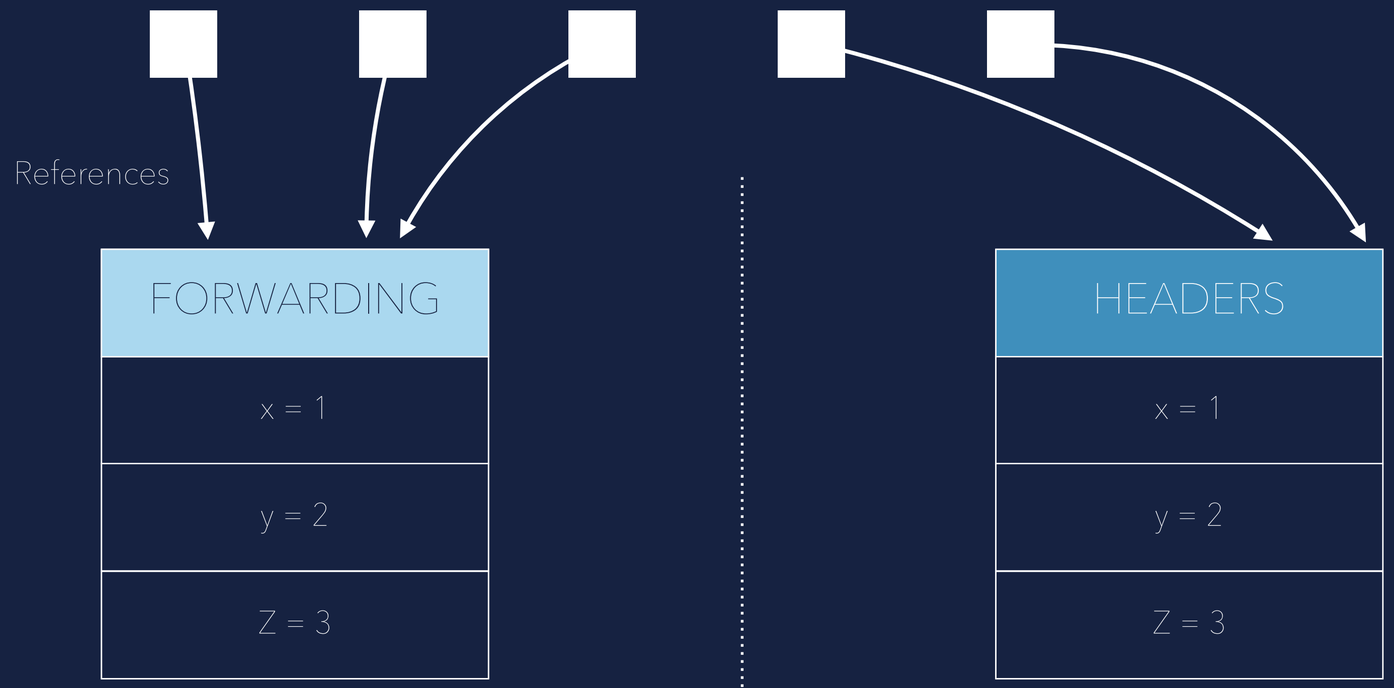


...when updating the references...

CONCURRENCY IS HARD...

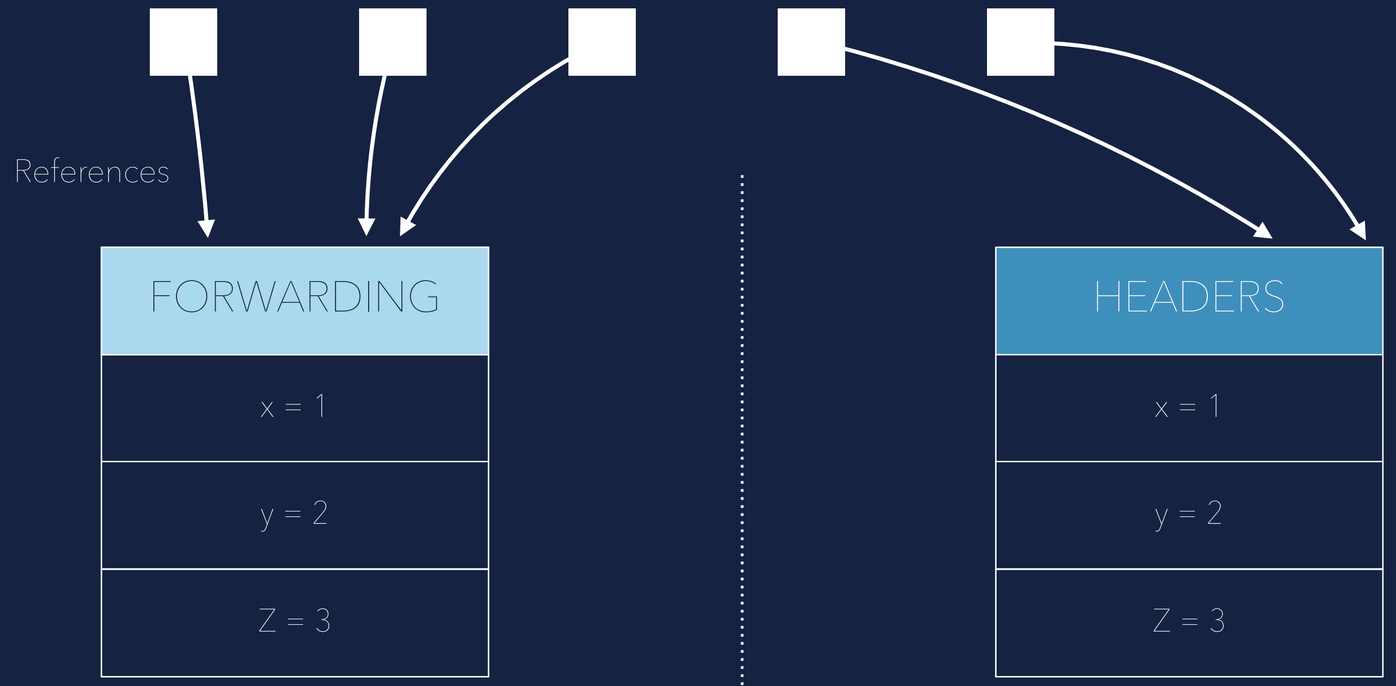
Concurrent copying



...both Objects are reachable !

CONCURRENCY IS HARD...

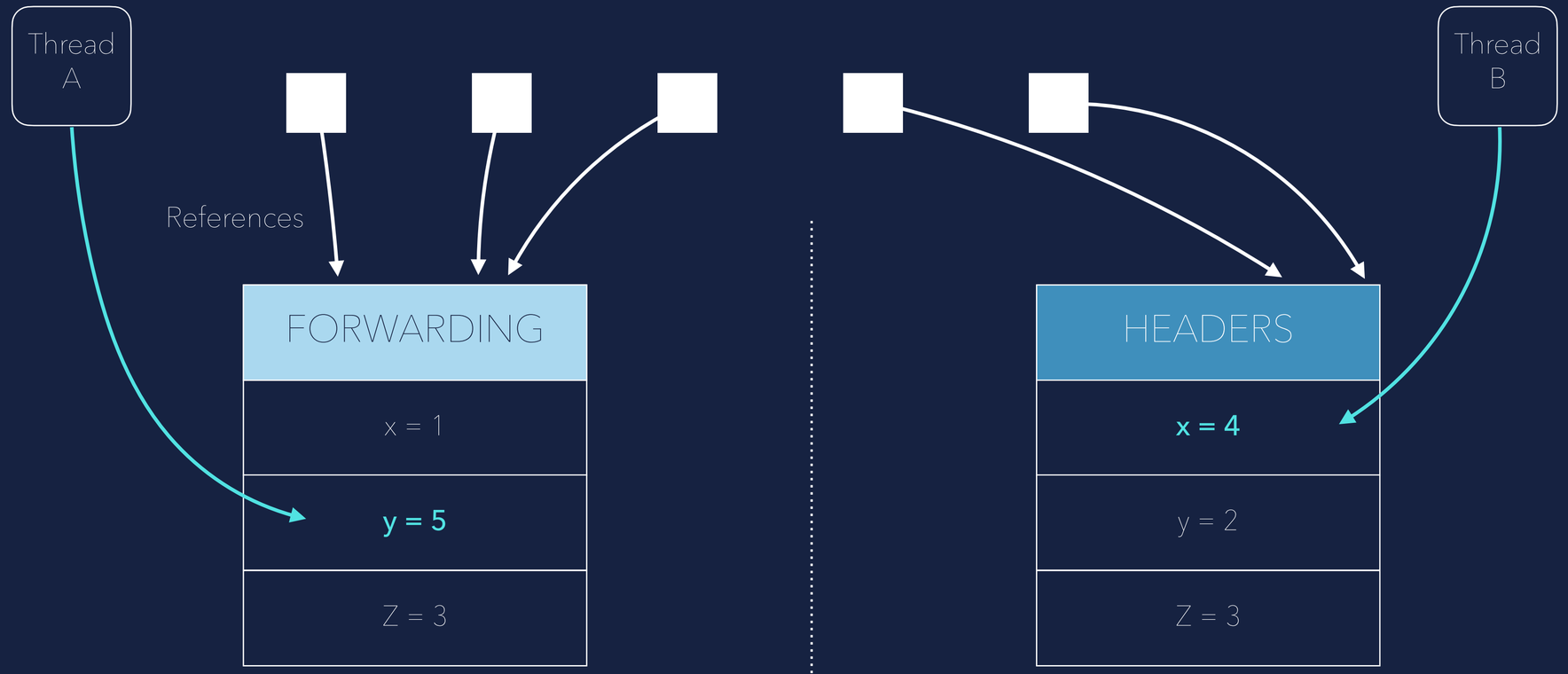
Concurrent copying



...both Objects are reachable !
And can be accessed in parallel by different Threads.

CONCURRENCY IS HARD...

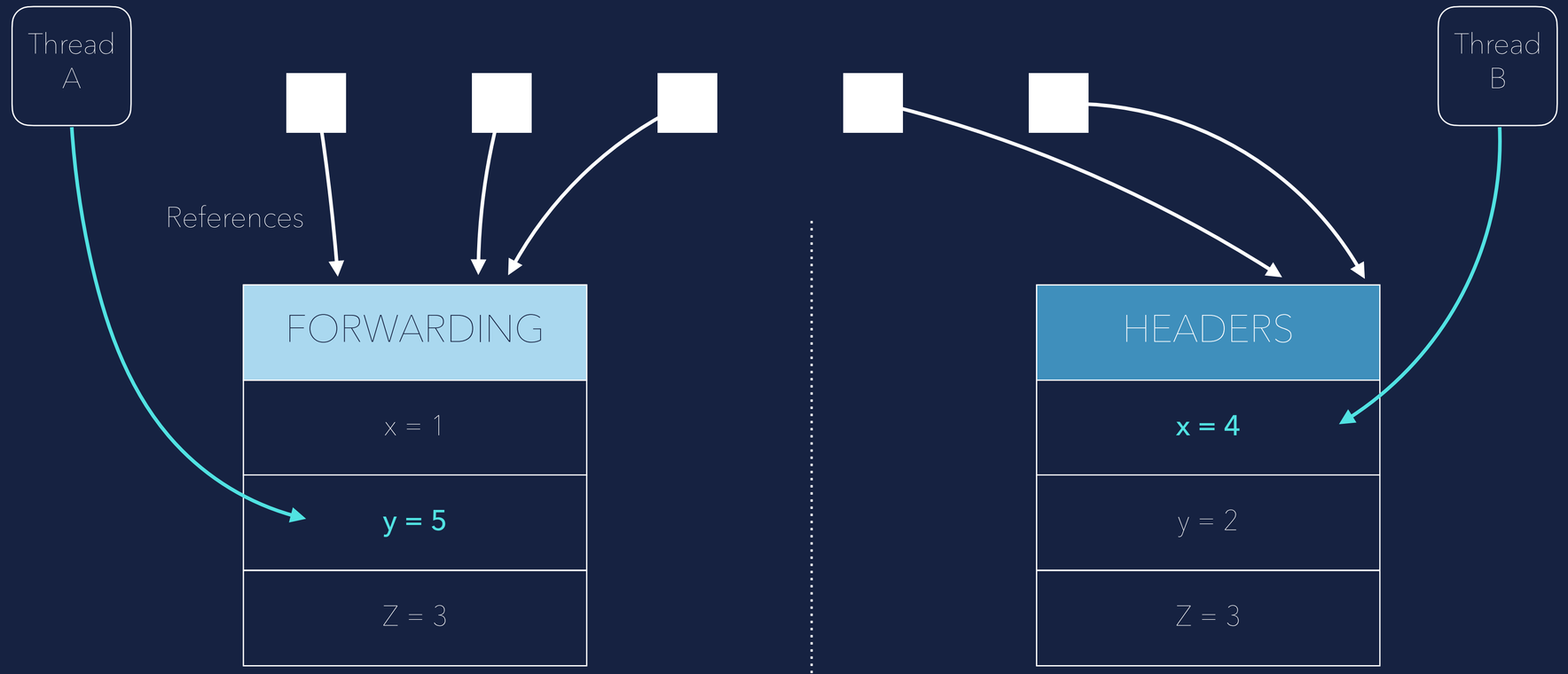
Concurrent copying



Threads can write to both Objects !

CONCURRENCY IS HARD...

Concurrent copying

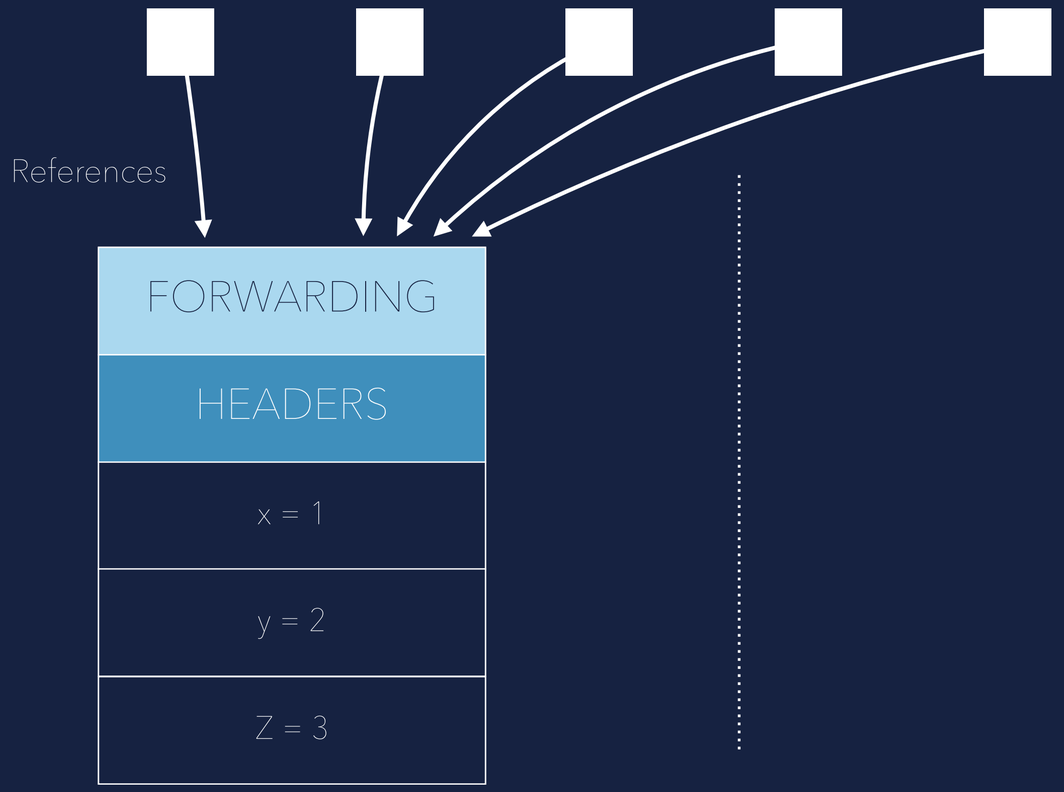


Threads can write to both Objects !

Which copy is correct ?

CONCURRENCY IS HARD...

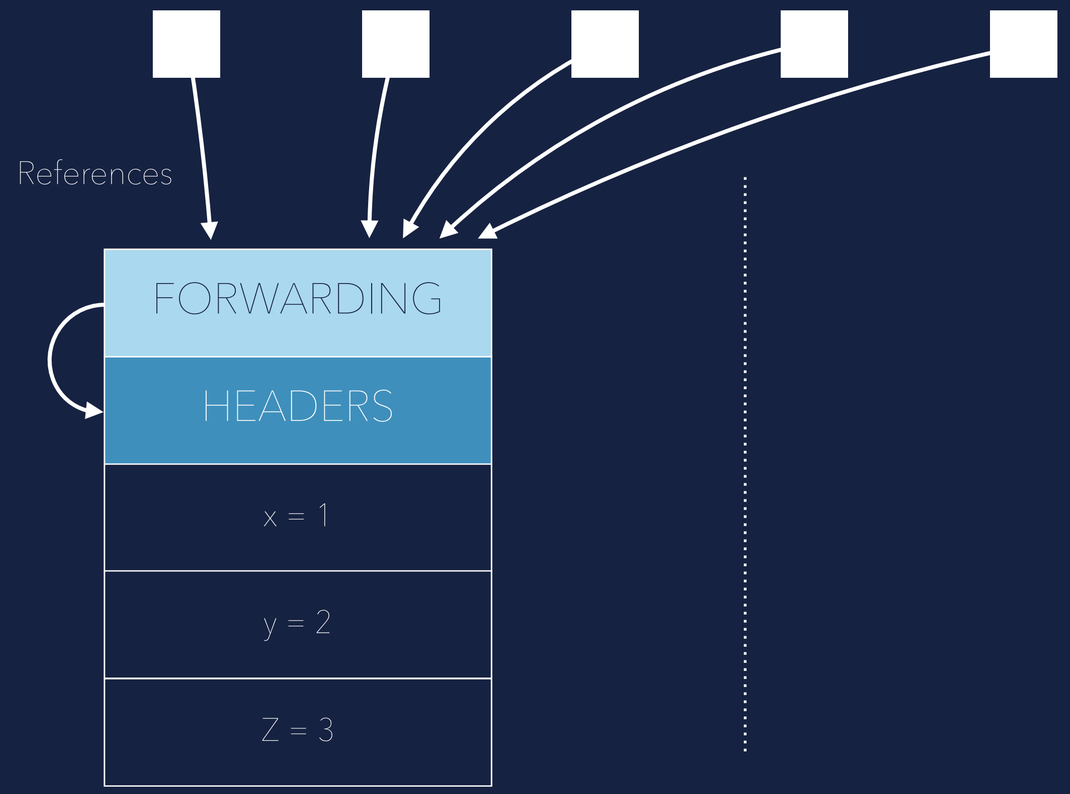
Concurrent copying



Solution could be installing a Brooks Pointer...

CONCURRENCY IS HARD...

Concurrent copying



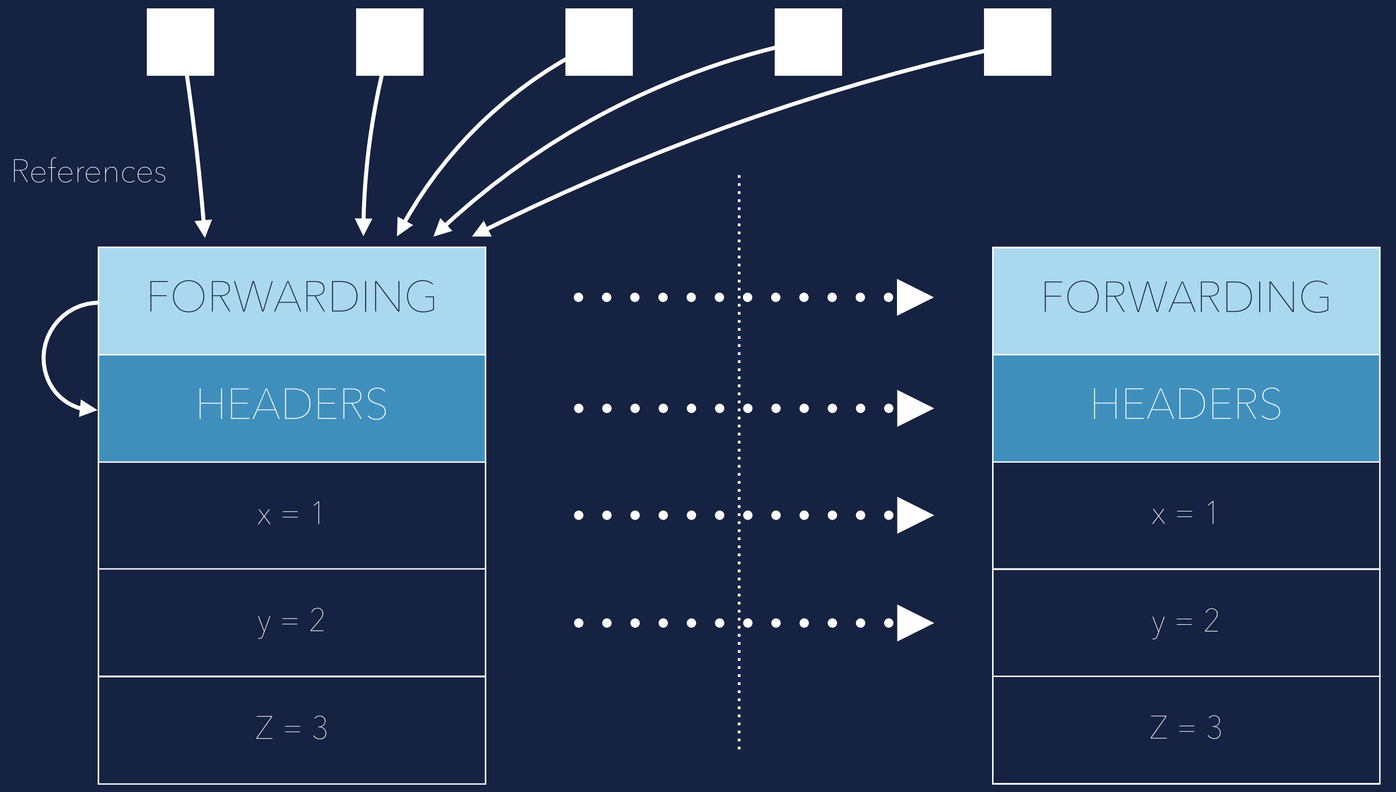
FROM Space

TO Space

...which points to object header itself

CONCURRENCY IS HARD...

Concurrent copying

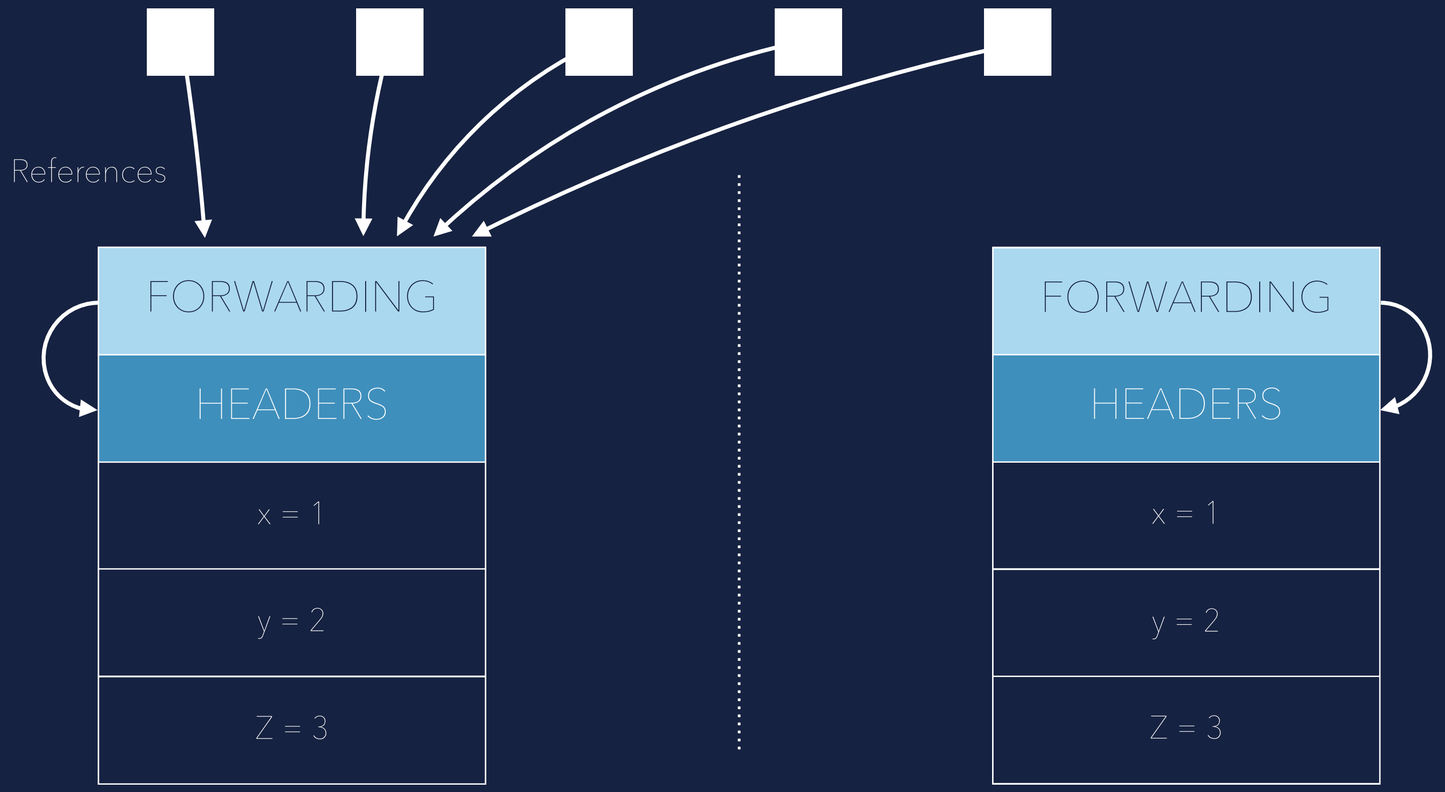


Atomic

Copy the Object

CONCURRENCY IS HARD...

Concurrent copying

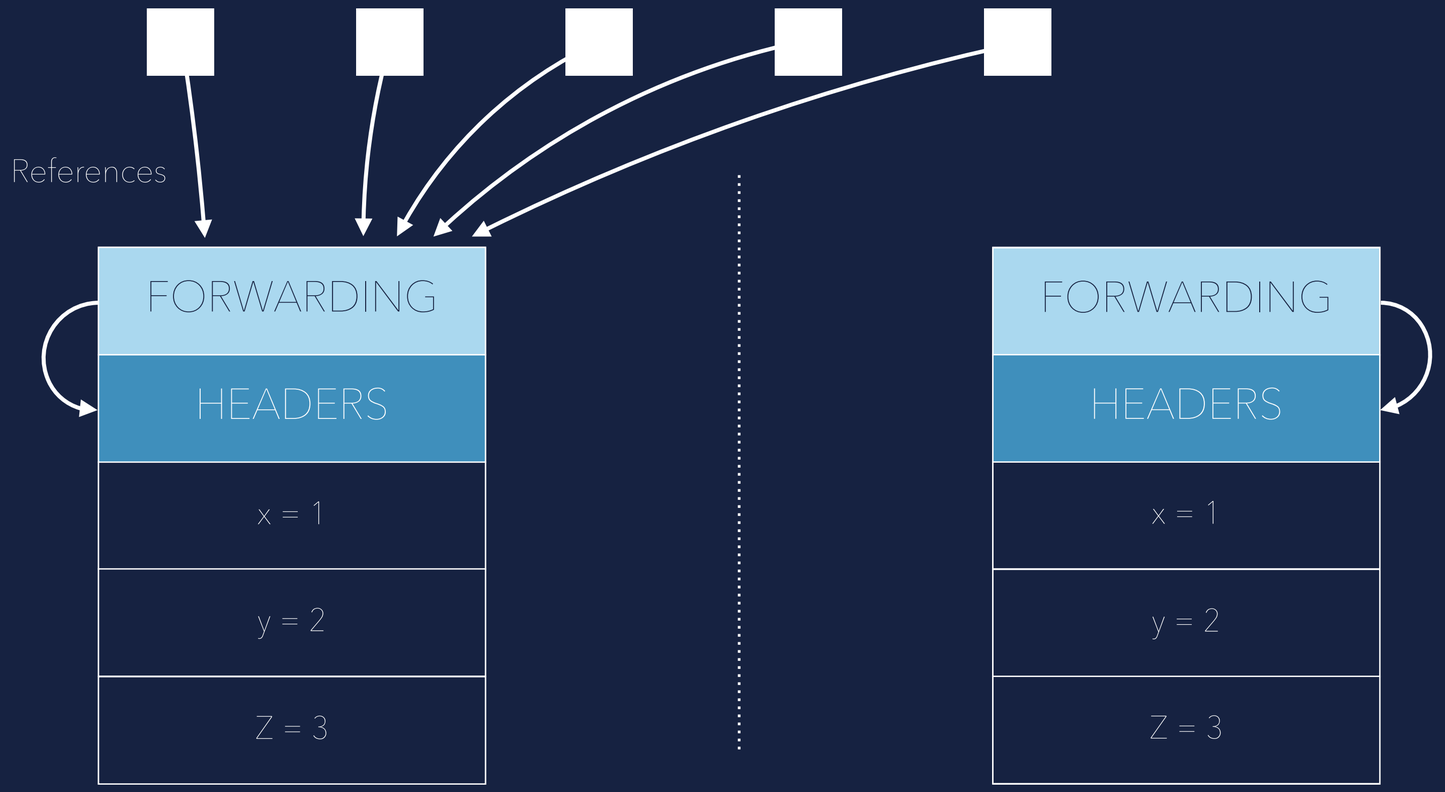


Atomic

Install forwarding pointer to itself

CONCURRENCY IS HARD...

Concurrent copying

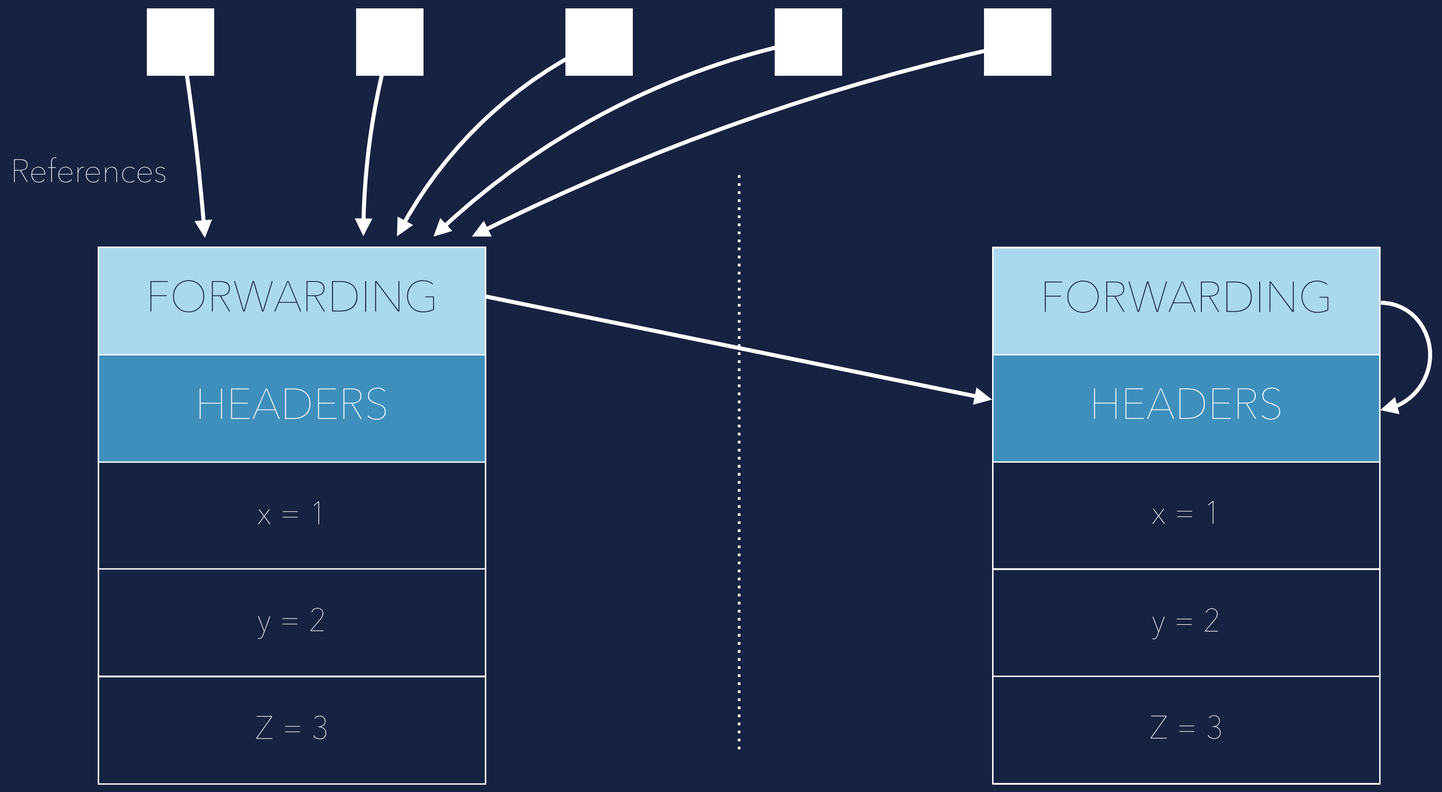


Atomic

Nobody knows about copy

CONCURRENCY IS HARD...

Concurrent copying

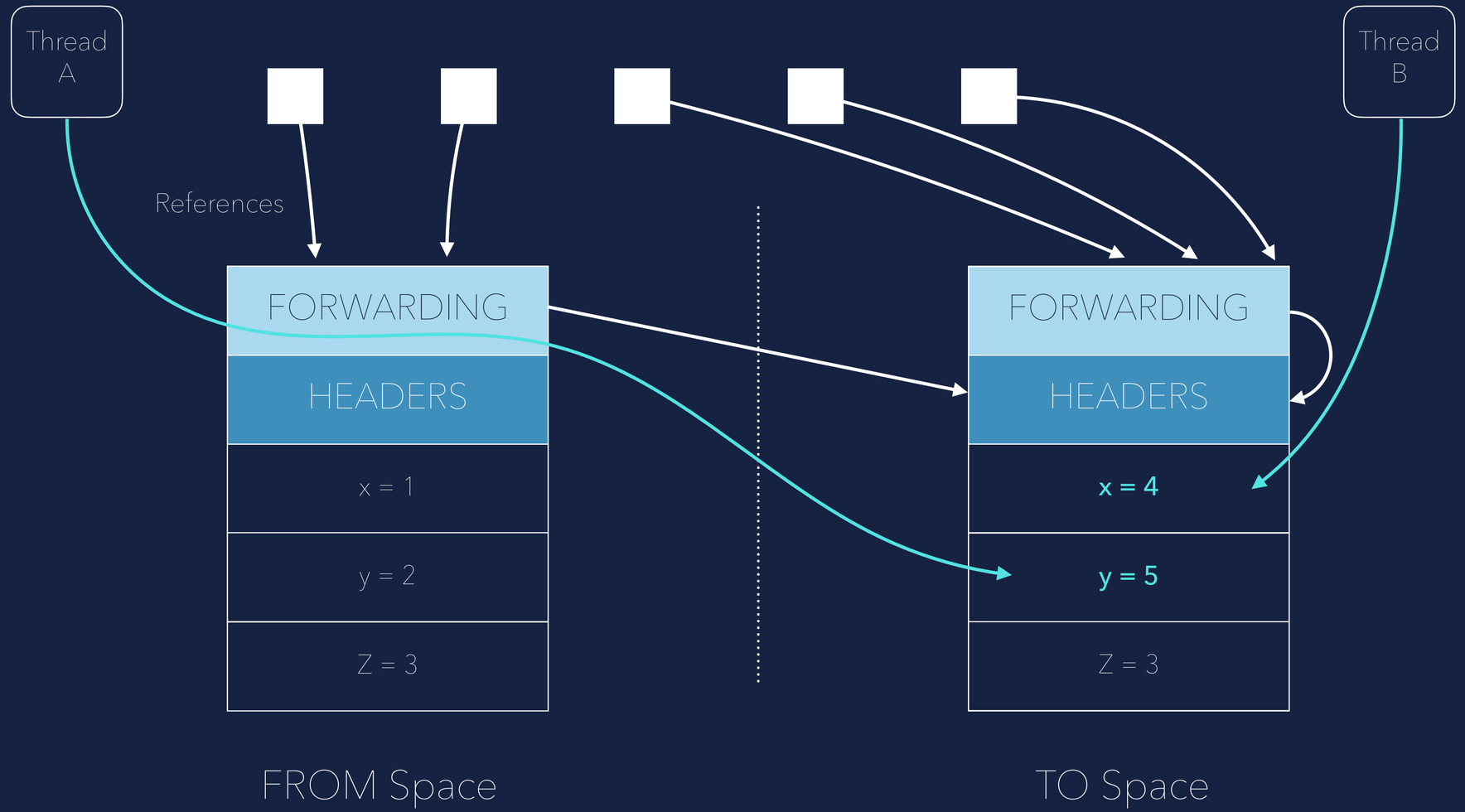


Atomic

Atomically update forwarding pointer of original object to new copy

CONCURRENCY IS HARD...

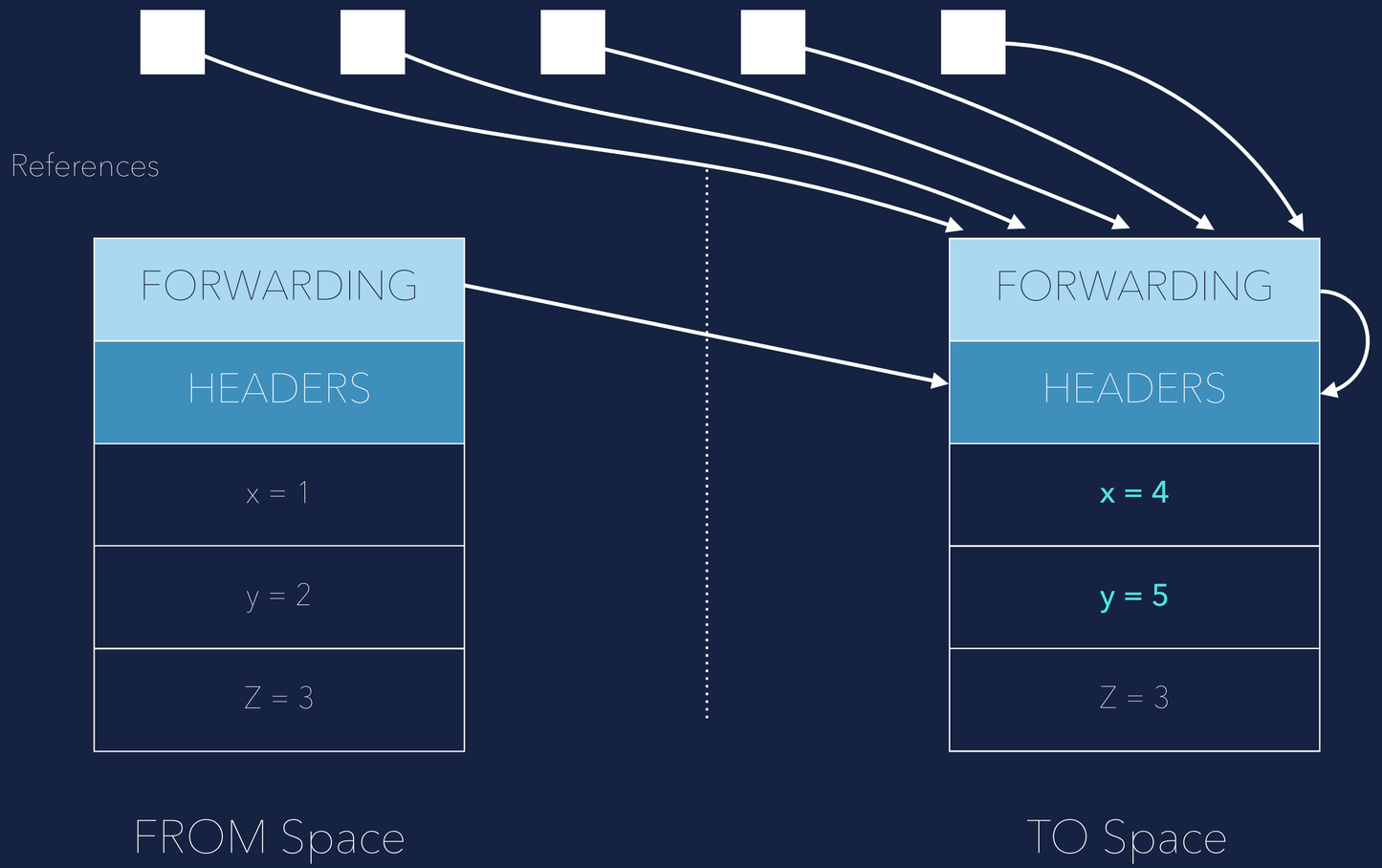
Concurrent copying



Threads now will always find the right object

CONCURRENCY IS HARD...

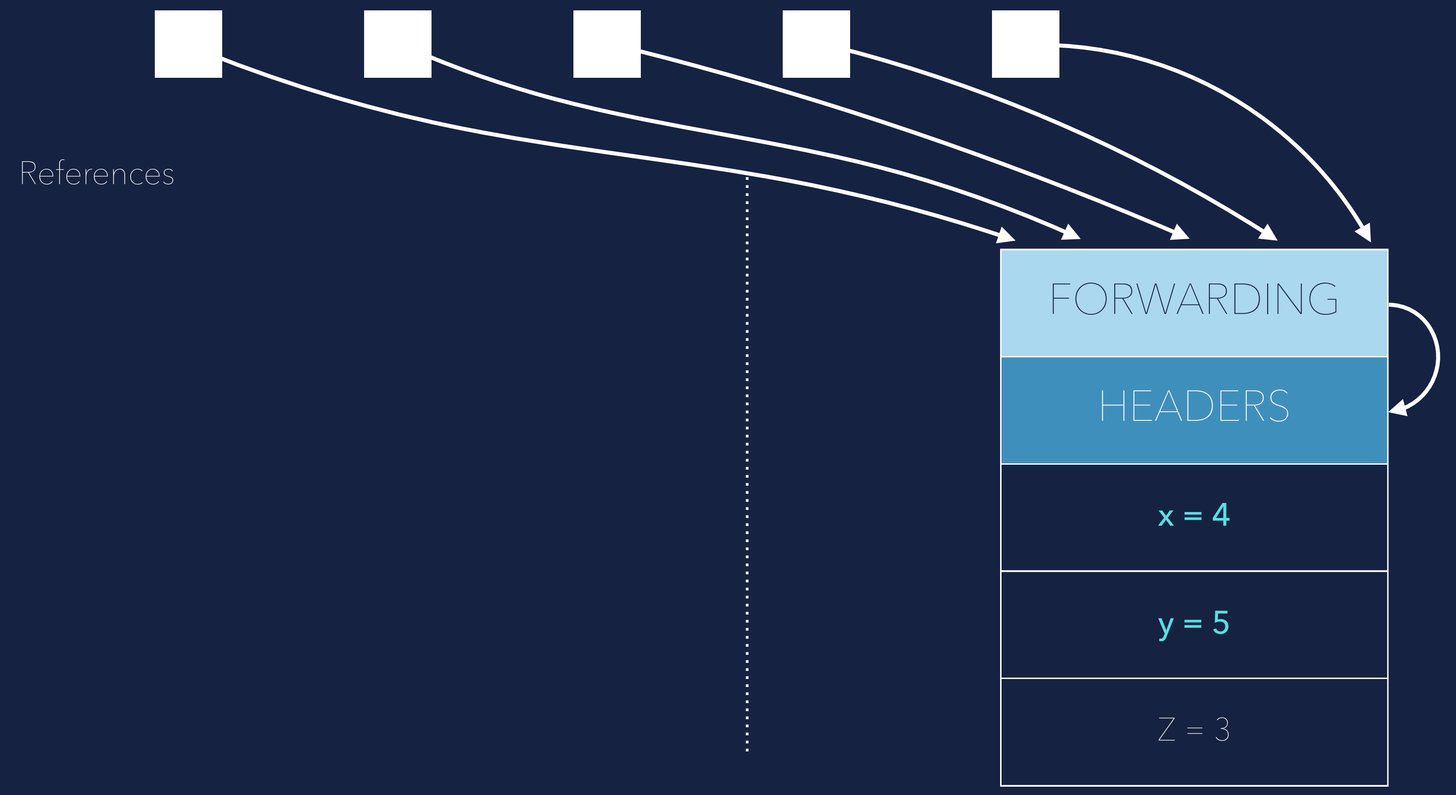
Concurrent copying



When all references are updated...

CONCURRENCY IS HARD...

Concurrent copying



COLLECTORS IN THE JVM

azul

SERIAL

SERIAL

AVAILABILITY	ALL JDK'S
PARALLEL	NO
CONCURRENT	NO
GENERATIONAL	YES
HEAP SIZE	SMALL - MEDIUM
PAUSE TIMES	LONGER
THROUGHPUT	LOW
LATENCY	HIGHER
CPU OVERHEAD	LOW (1-5%)

CHOOSE WHEN

- Single core systems with small heap (<4GB)
- No pause time requirements

BEST SUITED FOR

- Single threaded applications
- Development environments
- Microservices on small nodes

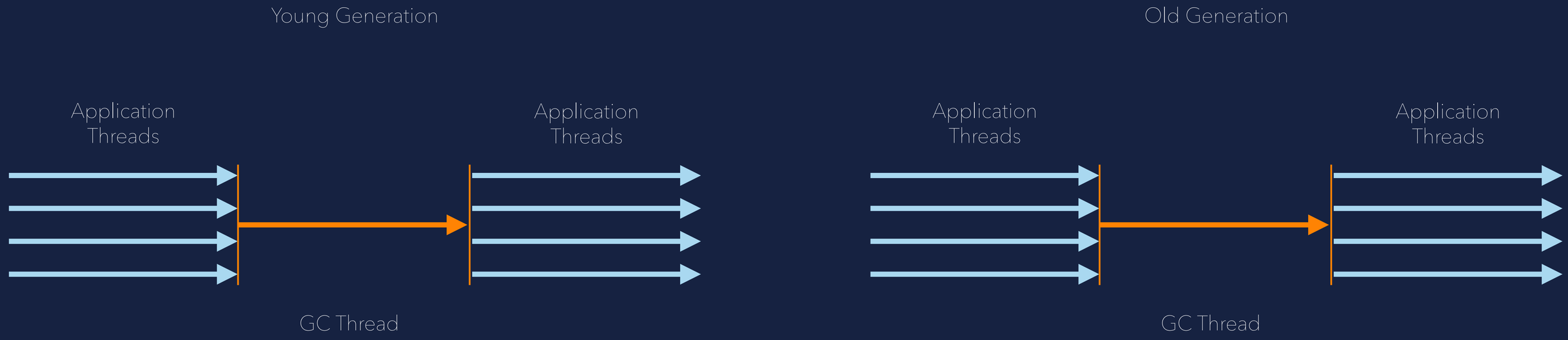
OS SUPPORT	
JVM SWITCH	`> java -XX:+UseSerialGC`

azul

SERIAL

NOTES

- Automatically selected if only a single processor is available
- Automatically selected if the avail. memory less than 1792 MB
- Mark and Compact



azul

PARALLEL

PARALLEL

AVAILABILITY	ALL JDK'S
PARALLEL	YES
CONCURRENT	NO
GENERATIONAL	YES
HEAP SIZE	MEDIUM - LARGE
PAUSE TIMES	MODERATE
THROUGHPUT	HIGH
LATENCY	LOWER
CPU OVERHEAD	MODERATE (5-10%)

CHOOSE WHEN

- Multi-core systems with small heap (<4GB)
- Peak performance is needed without pause time requirements

BEST SUITED FOR

- Batch processing
- Scientific computing
- Data analysis

OS SUPPORT	
JVM SWITCH	`> java -XX:+UseParallelGC/-XX:+UseParallelOldGC`

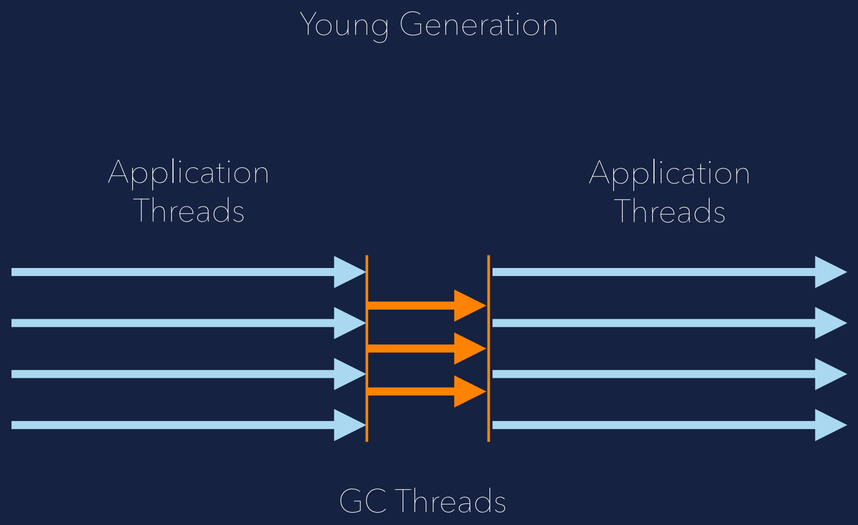
azul

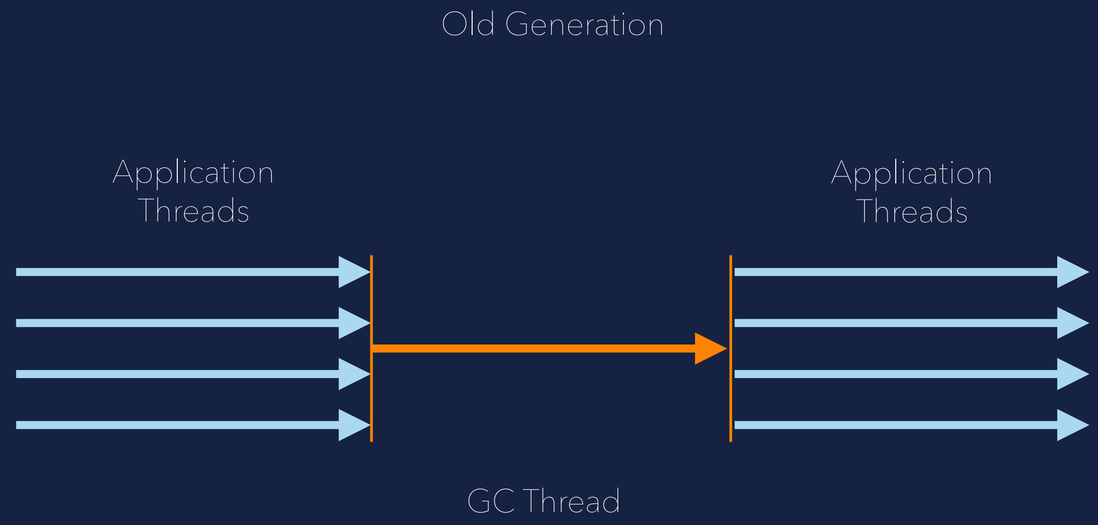
PARALLEL

NOTES

- Default garbage collector from JDK 5 to JDK 8
- Mark and Compact

`-XX:+UseParallelGC`





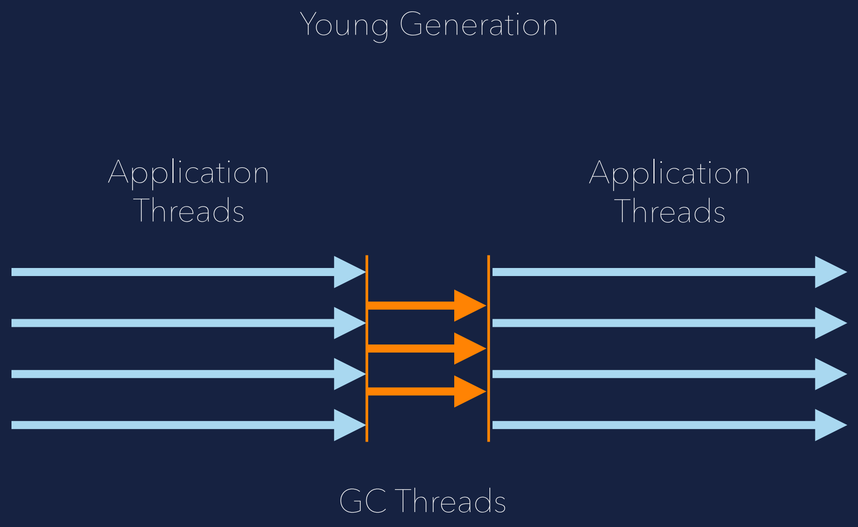
azul

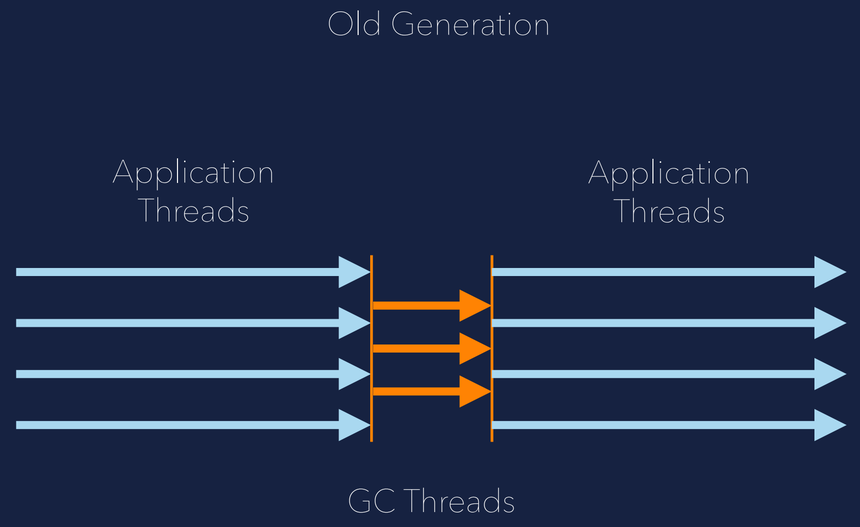
PARALLEL

NOTES

- Default garbage collector from JDK 5 to JDK 8
- Mark and Compact

`-XX:+UseParallelOldGC`





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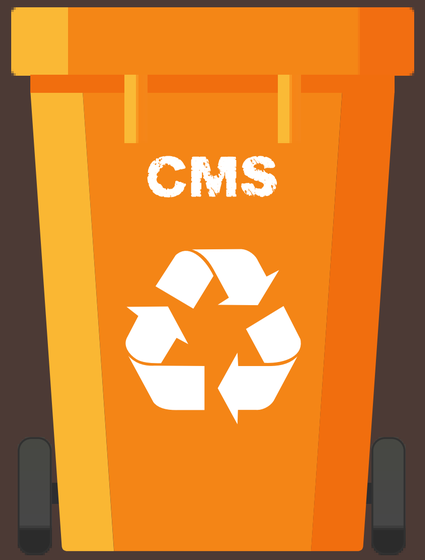


CMS

Concurrent Mark and Sweep

DEPRECATED

CMS

AVAILABILITY	JDK 1.4 - 13
PARALLEL	YES
CONCURRENT	PARTIALLY
GENERATIONAL	YES
HEAP SIZE	MEDIUM - LARGE
PAUSE TIMES	MODERATE
THROUGHPUT	MODERATE
LATENCY	MODERATE
CPU OVERHEAD	MODERATE (5-15%)

CHOOSE WHEN

- Response time is more important than throughput
- Pause time must be kept shorter than 1 sec

BEST SUITED FOR

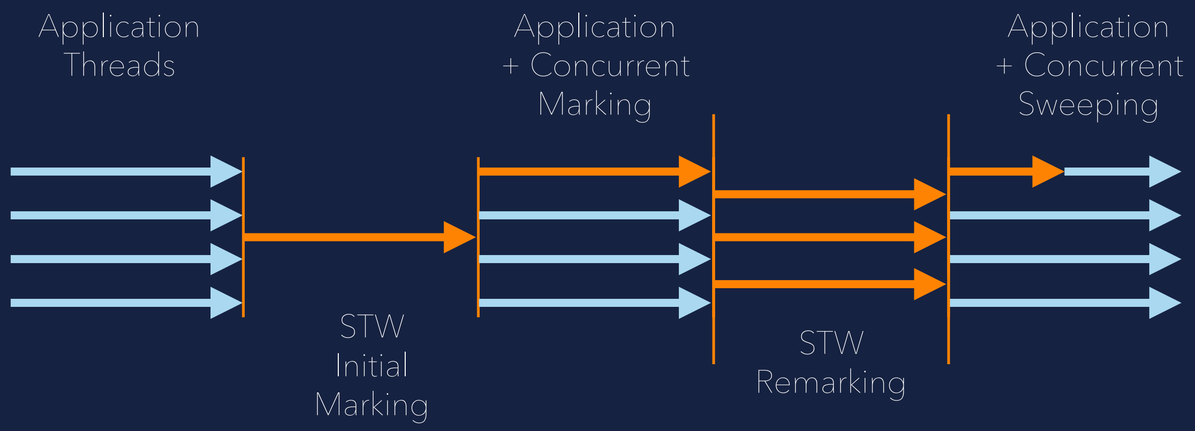
- Web applications
- Mediums sized enterprise systems

OS SUPPORT	
JVM SWITCH	`> java -XX:+UseConcMarkSweepGC`

CMS

NOTES

- Deprecated as of JDK 9
- Removed from JDK 14
- Concurrent marking but no compaction -> Fragmentation



G1

Garbage First

G1

Heap-Layout

Region size 1 - 32 MB

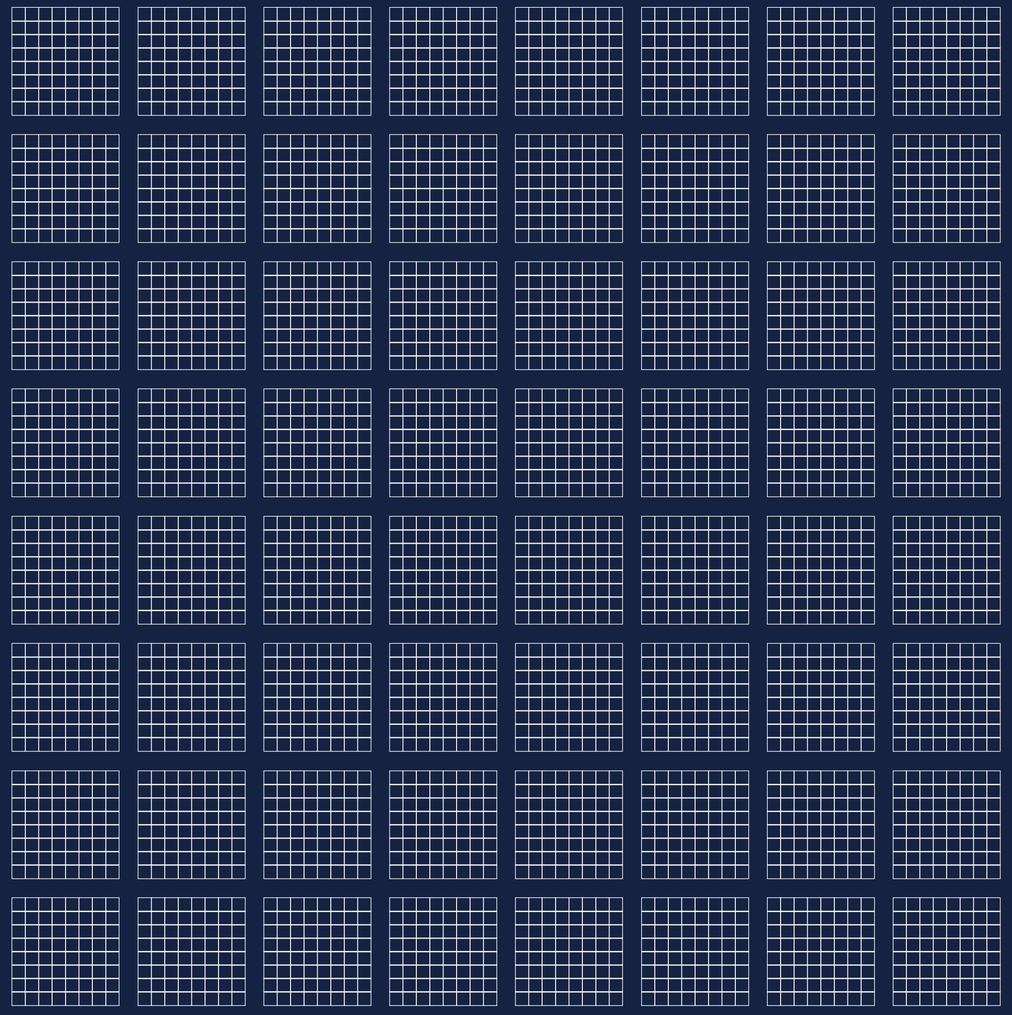
Max no. of region <= 2048

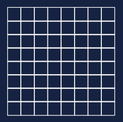
Heap	Region
< 4 GB	1 MB
< 8 GB	2 MB
< 16 GB	4 MB
< 32 GB	8 MB
< 64 GB	16 MB
> 64 GB	32 MB

Example 8GB Heap:

8 GB Heap = 8192 MB

8192 MB / 2048 = 4 MB region size





Unassigned region

azul

G1

Heap-Layout

Region size 1 - 32 MB

Max no. of region <= 2048

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< 8 GB	2 MB
< 16 GB	4 MB
< 32 GB	8 MB
< 64 GB	16 MB
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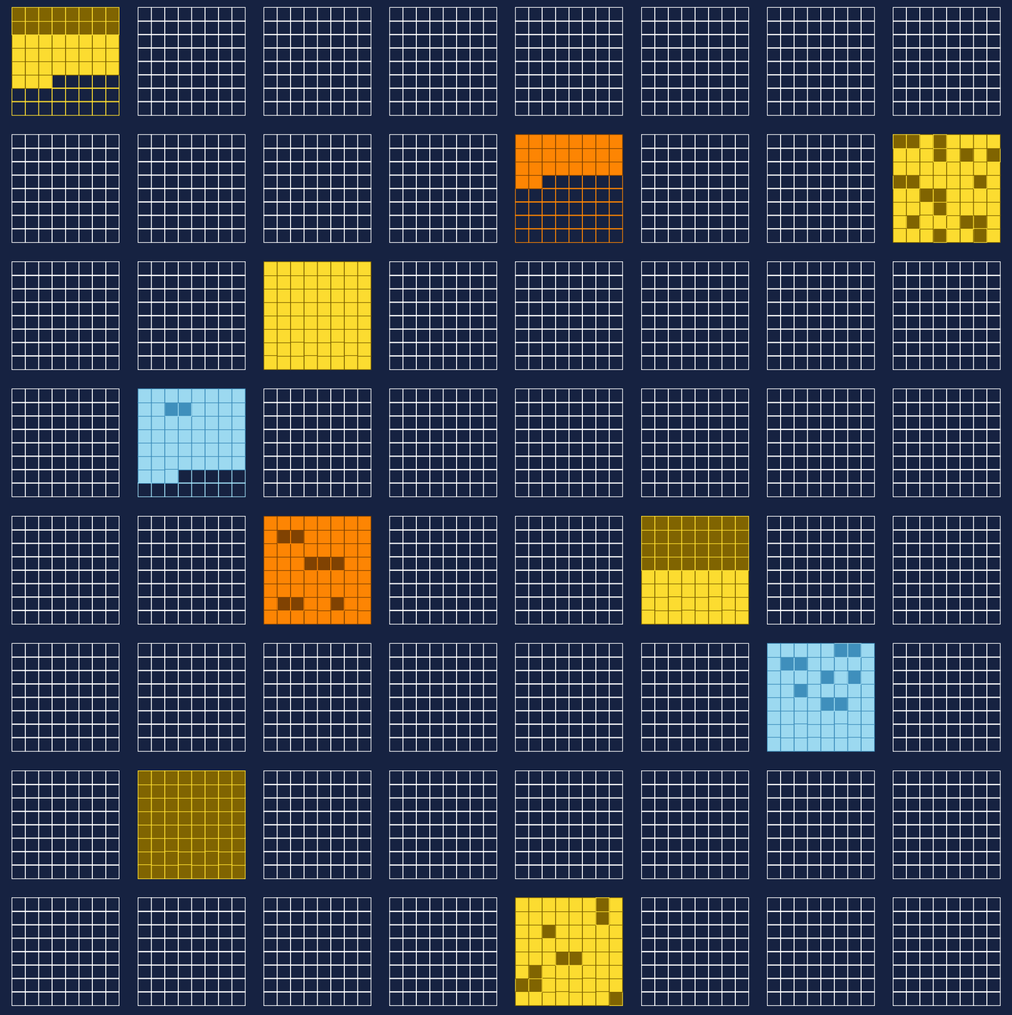

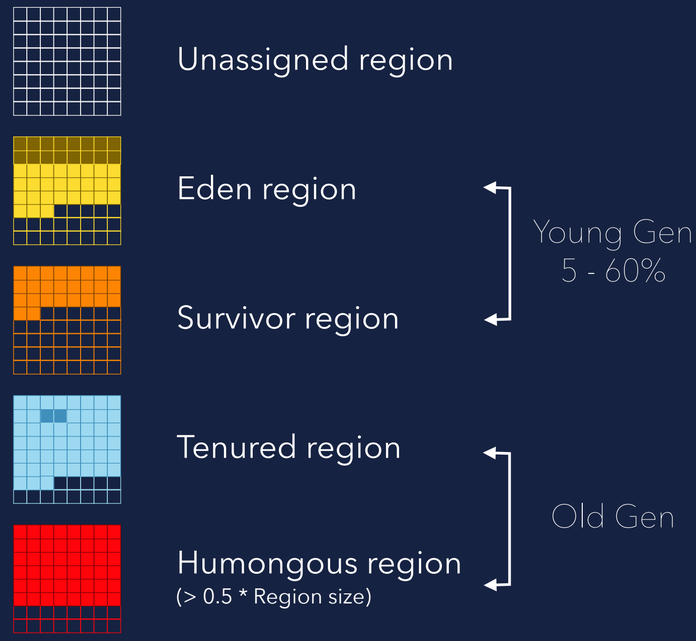

azul

G1

Heap-Layout

Region size 1 - 32 MB

Max no. of region <= 2048

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Example 8GB Heap:

8 GB Heap = 8192 MB

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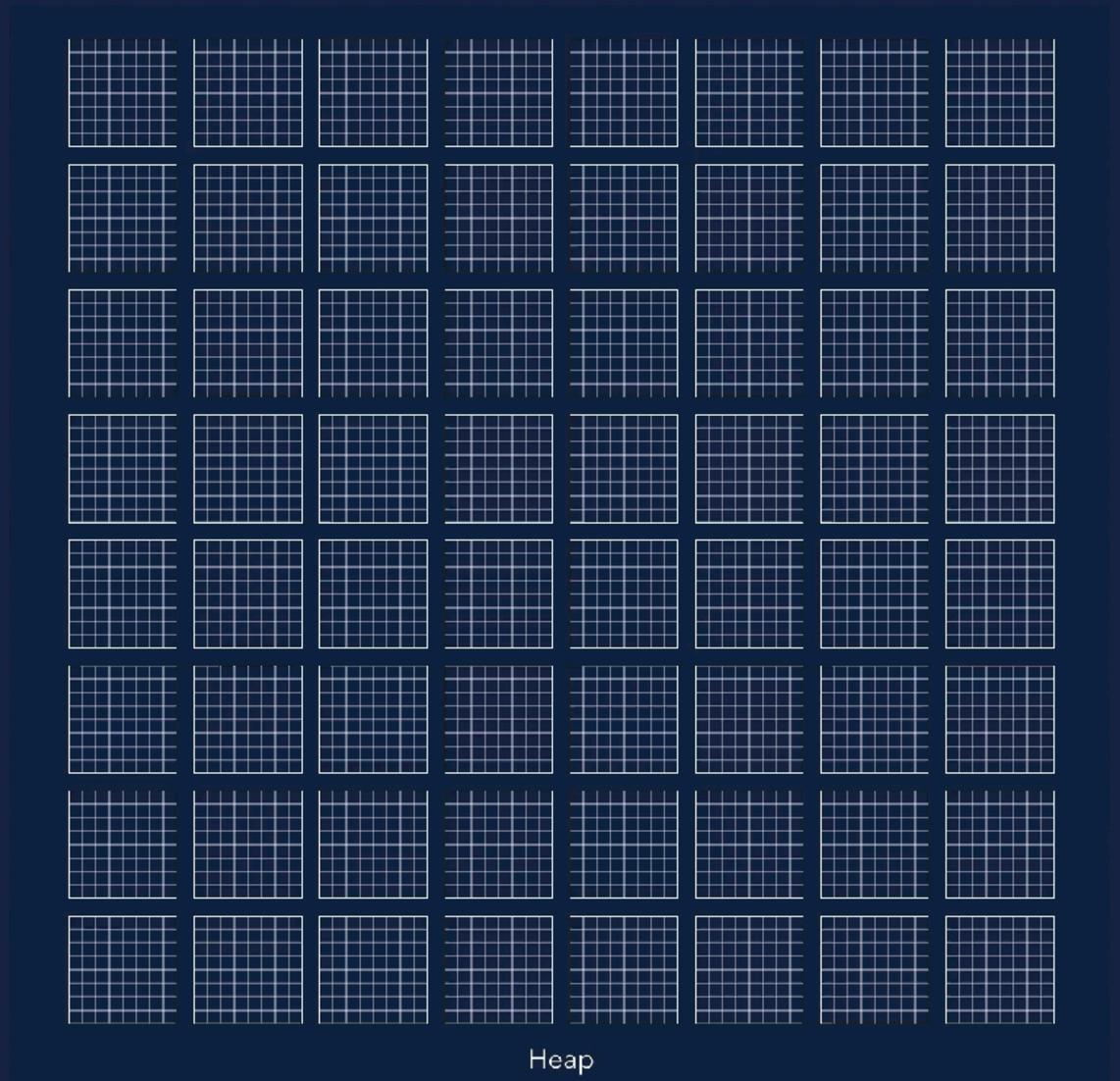


Unassigned region

Eden region

Survivor region

Young Gen
5 - 60%

Tenured region

Humongous region
(> 0.5 * Region size)

Old Gen

Example:
6 Eden Regions
3 Survivor Regions

2 Regions with most garbage will be collected/promoted

azul

G1

AVAILABILITY	JDK 7U4+
PARALLEL	YES
CONCURRENT	PARTIALLY
GENERATIONAL	YES
HEAP SIZE	MEDIUM - LARGE
PAUSE TIMES	SHORT - MEDIUM
THROUGHPUT	HIGH
LATENCY	LOWER
CPU OVERHEAD	MODERATE (5-15%)

CHOOSE WHEN

- Response time is more important than throughput
- Pause time should be around 200 ms
- Heap size is not larger than 16-32 GB

BEST SUITED FOR

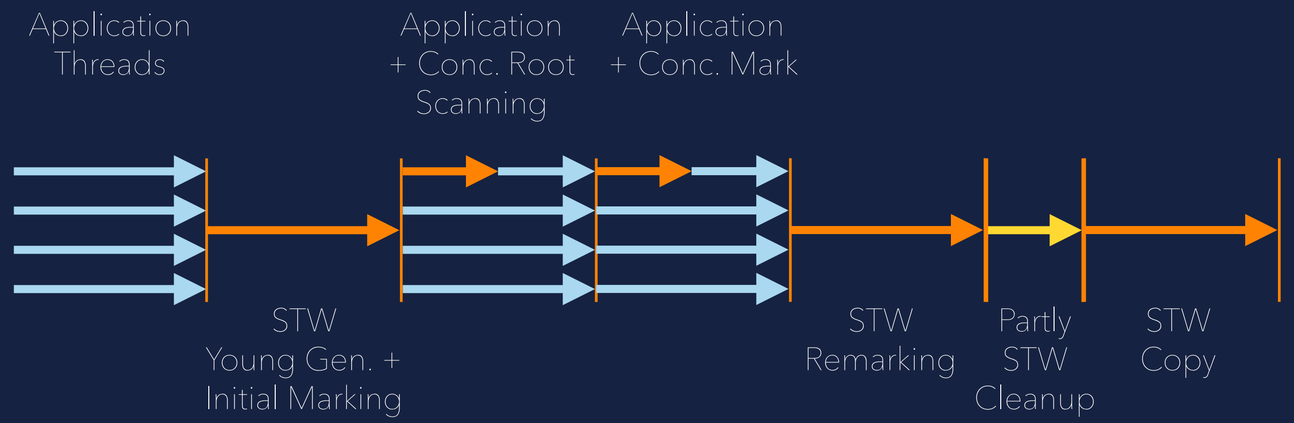
- Mixed workloads
- Large sized enterprise systems
- Responsive in medium to large heaps

OS SUPPORT	
JVM SWITCH	`> java -XX:+UseG1GC`

G1

NOTES

- Default collector from JDK 9 onwards
- Concurrent marking



azul

EPSILON

EPSILON

AVAILABILITY	JDK 11+
PARALLEL	-
CONCURRENT	-
GENERATIONAL	-
HEAP SIZE	-
PAUSE TIMES	-
THROUGHPUT	VERY HIGH
LATENCY	VERY LOW
CPU OVERHEAD	VERY LOW

CHOOSE WHEN

- Testing performance or memory pressure
- Highest performance is needed and nearly no garbage is created

BEST SUITED FOR

- Extremely short lived jobs
- Last drop latency improvements
- Last drop throughput improvements

OS SUPPORT	
JVM SWITCH	`> java -XX:+UnlockExperimentalVMOptions -XX:+UseEpsilonGC`

azul

SHENANDOAH

azul

SHENANDOAH

AVAILABILITY	JDK 11.0.9+ / JDK 24
PARALLEL	YES
CONCURRENT	FULLY
GENERATIONAL	NO / YES
HEAP SIZE	MEDIUM - LARGE
PAUSE TIMES	SHORT
THROUGHPUT	VERY HIGH
LATENCY	VERY LOW
CPU OVERHEAD	MODERATE (10-20%)

CHOOSE WHEN

- Response time is a high priority
- Using a very large heap (100GB+)
- Predictable response times needed

BEST SUITED FOR

- Latency sensitive applications
- Large scale systems
- Highly concurrent applications

OS SUPPORT	
JVM SWITCH	`> java -XX:+UseShenandoahGC`

azul

SHENANDOAH

NOTES

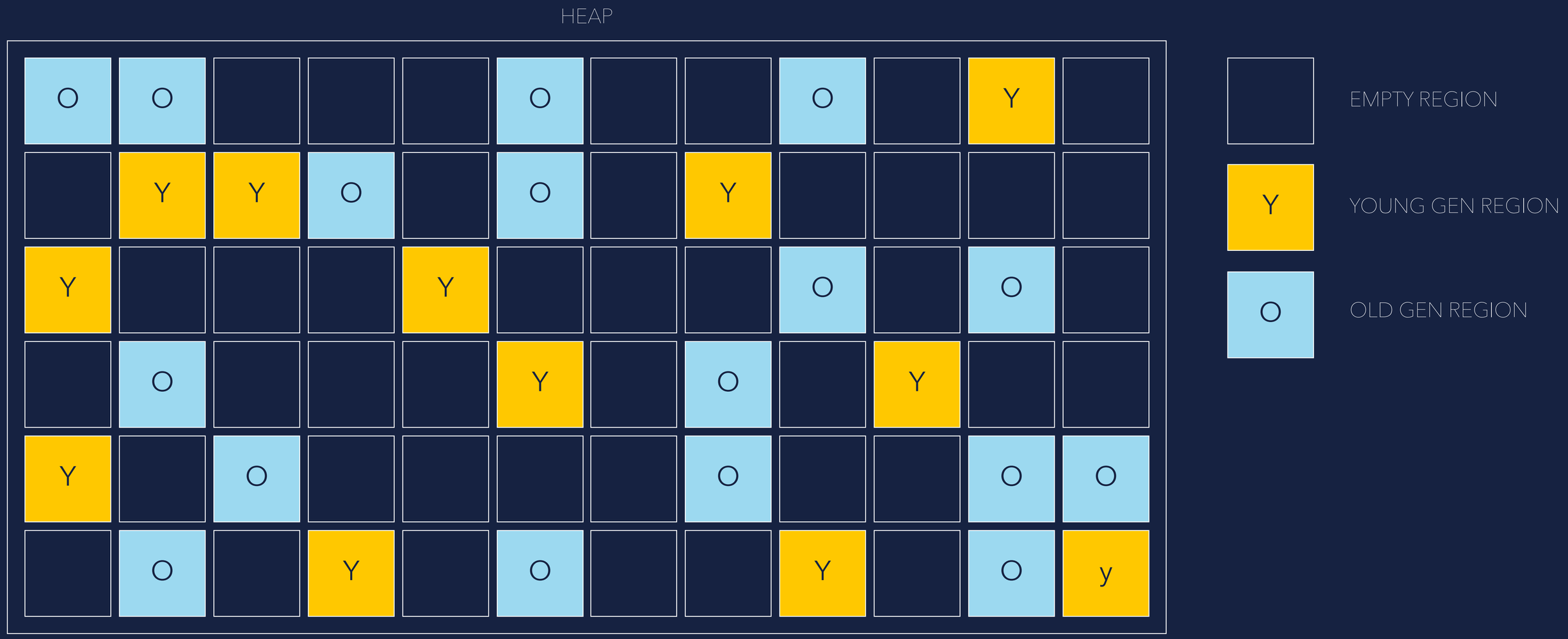
- Not available in Oracle JDK
- A bit reduced throughput due to concurrent GC
- Makes use of new barrier concept, load reference barrier
- First generational version in JDK 24

ZGC

Z Garbage Collector

ZGC

Heap-Layout



azul

ZGC

AVAILABILITY	JDK 15-23 / JDK 21+
PARALLEL	YES
CONCURRENT	FULLY
GENERATIONAL	NO / YES
HEAP SIZE	LARGE
PAUSE TIMES	SHORT
THROUGHPUT	VERY HIGH
LATENCY	VERY LOW
CPU OVERHEAD	MODERATE (10-20%)

CHOOSE WHEN

- Response time is a high priority
- Using a very large heap (100GB+)
- Predictable response times needed

BEST SUITED FOR

- Low latency sensitive applications
- Large scale systems
- Highly concurrent applications

OS SUPPORT	
JVM SWITCH	`> java -XX:+UseZGC`

ZGC

NOTES

- Non-generational version removed in JDK 24

azul

C4

Concurrent Continues Compacting Collector

azul

C4

NOTES

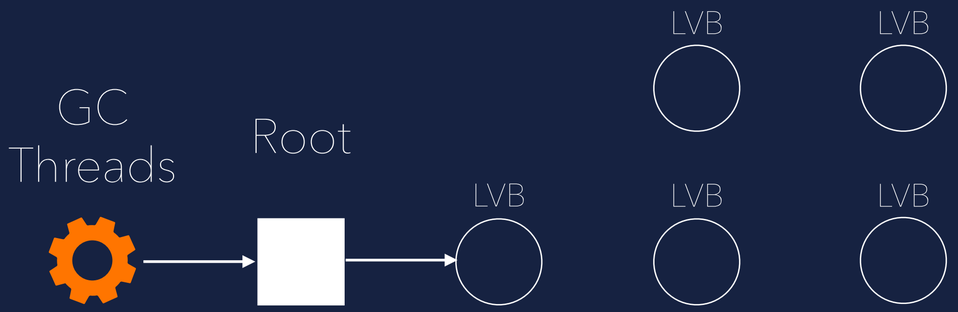
- Part of Azul Zing JVM
- Makes use of Loaded Value Barrier (LVB) everywhere
  (Test + Jump which only takes 1 cpu cycle -> very fast)
- LVB is read and write barrier
  (guaranteed to be hit on every access)
- Best performance by using Transparent Huge Pages
  (Normal page size 4kB, THP size 2MB)

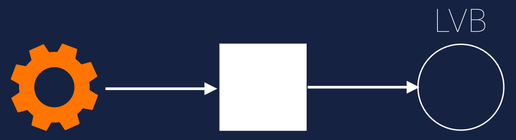
C4

MARKING PHASE

C4

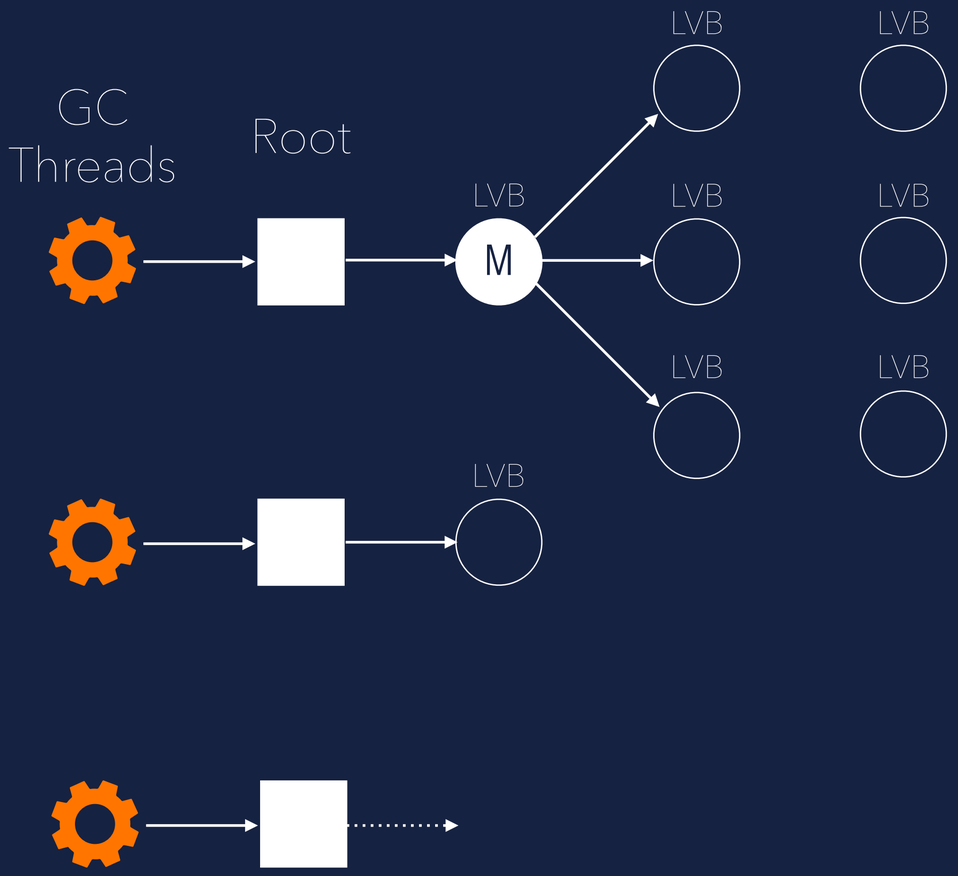
Marking Phase





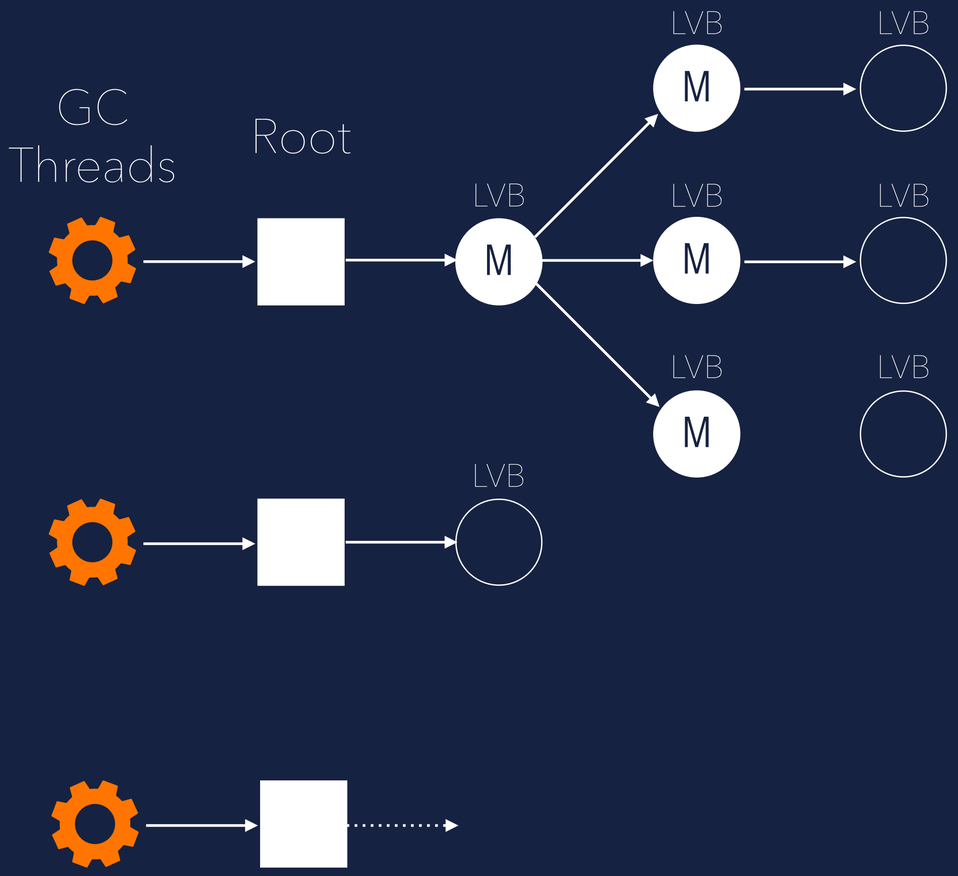
C4

Marking Phase



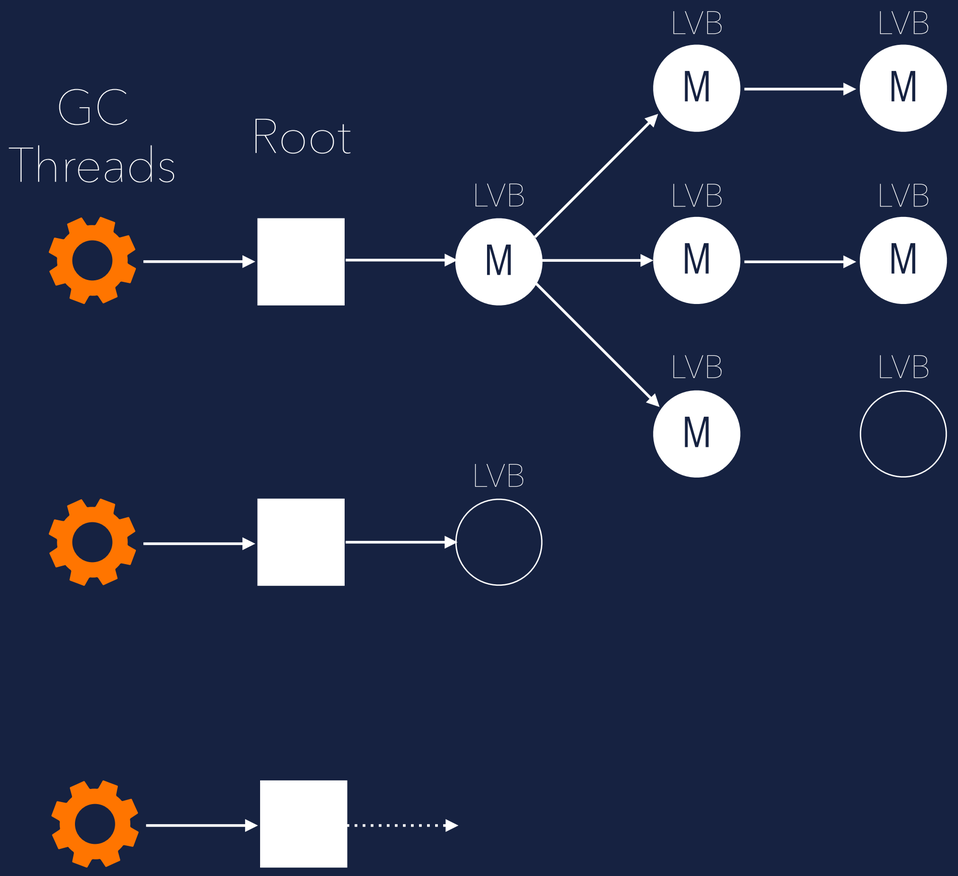
C4

Marking Phase



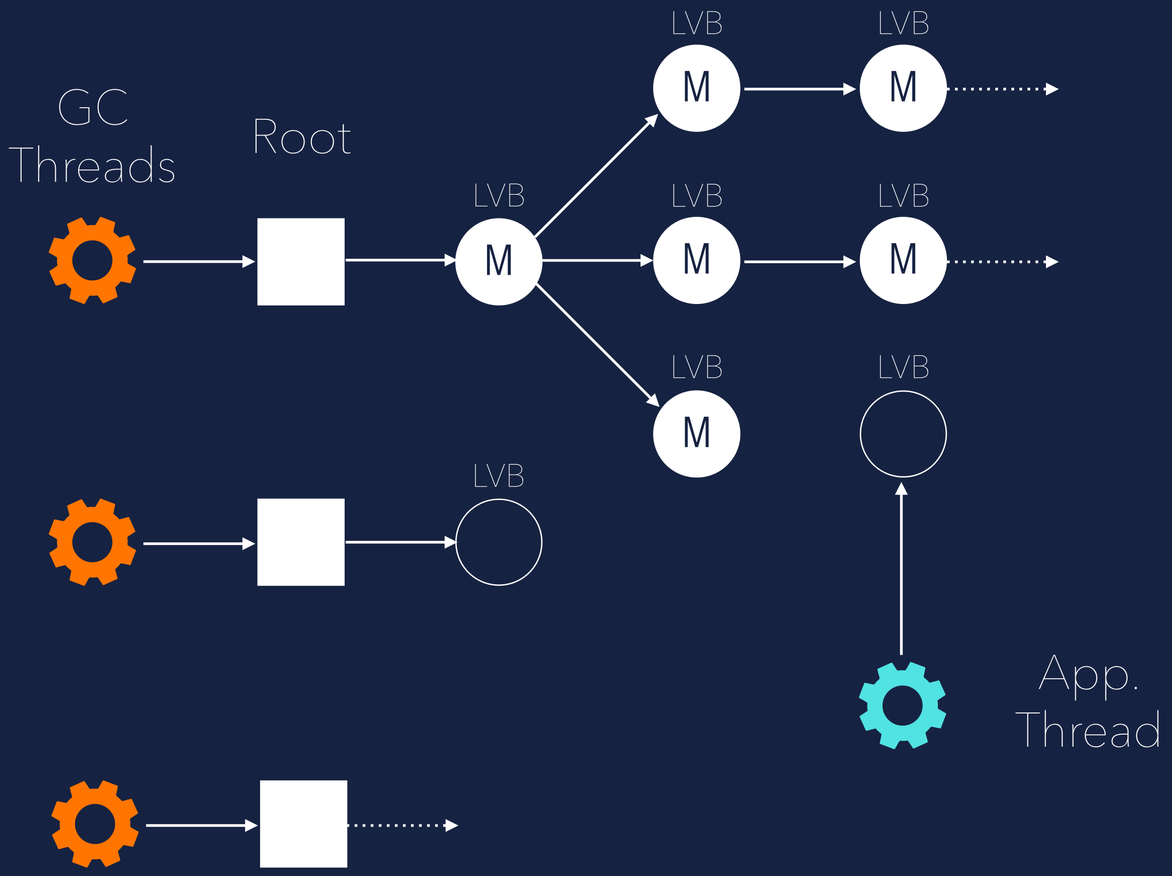
C4

Marking Phase



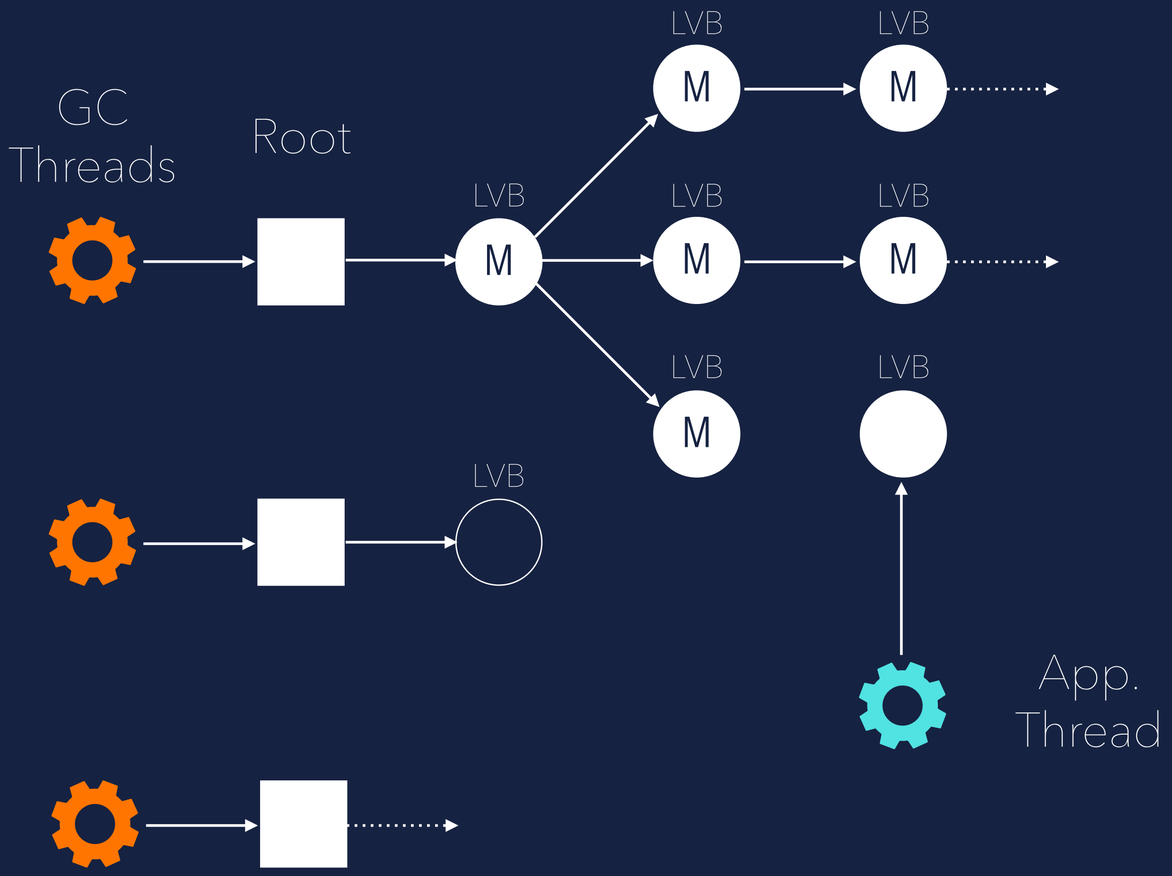
C4

Marking Phase



C4

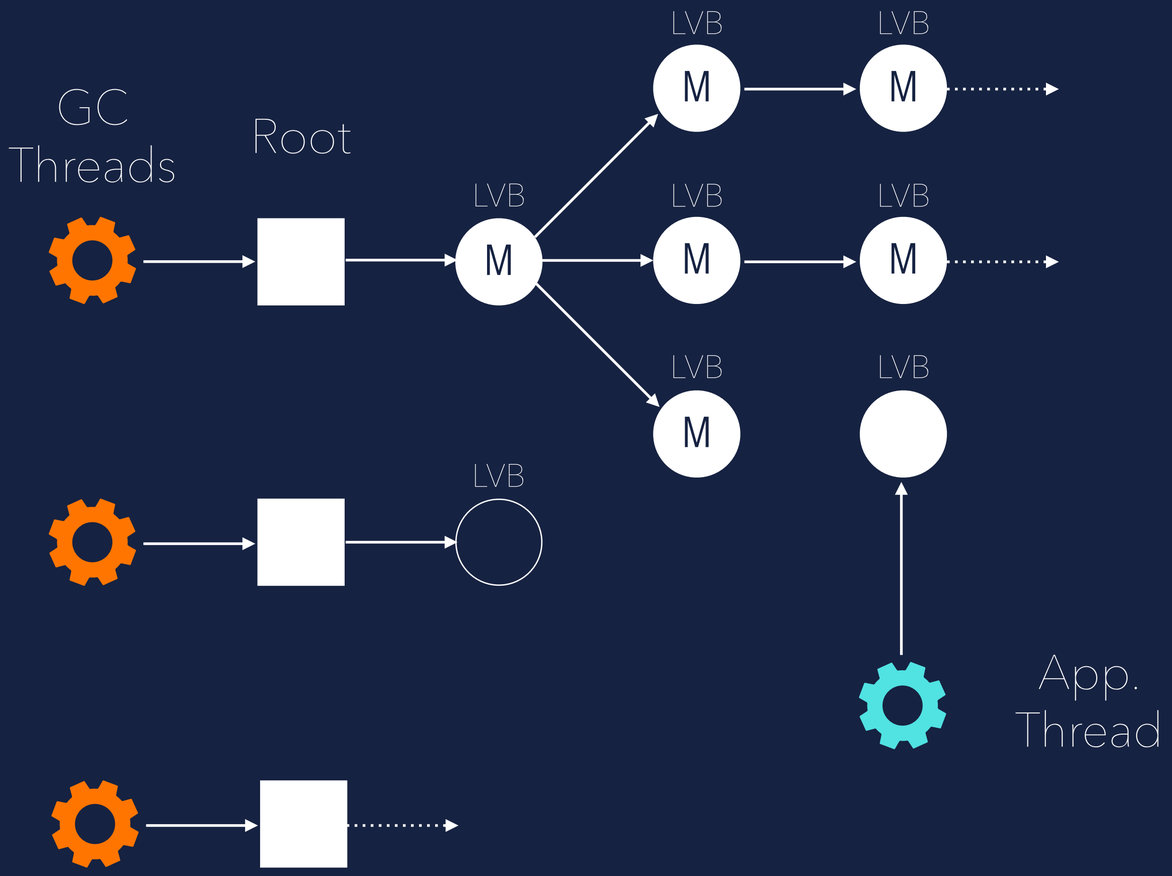
Marking Phase



Trigger LVB

C4

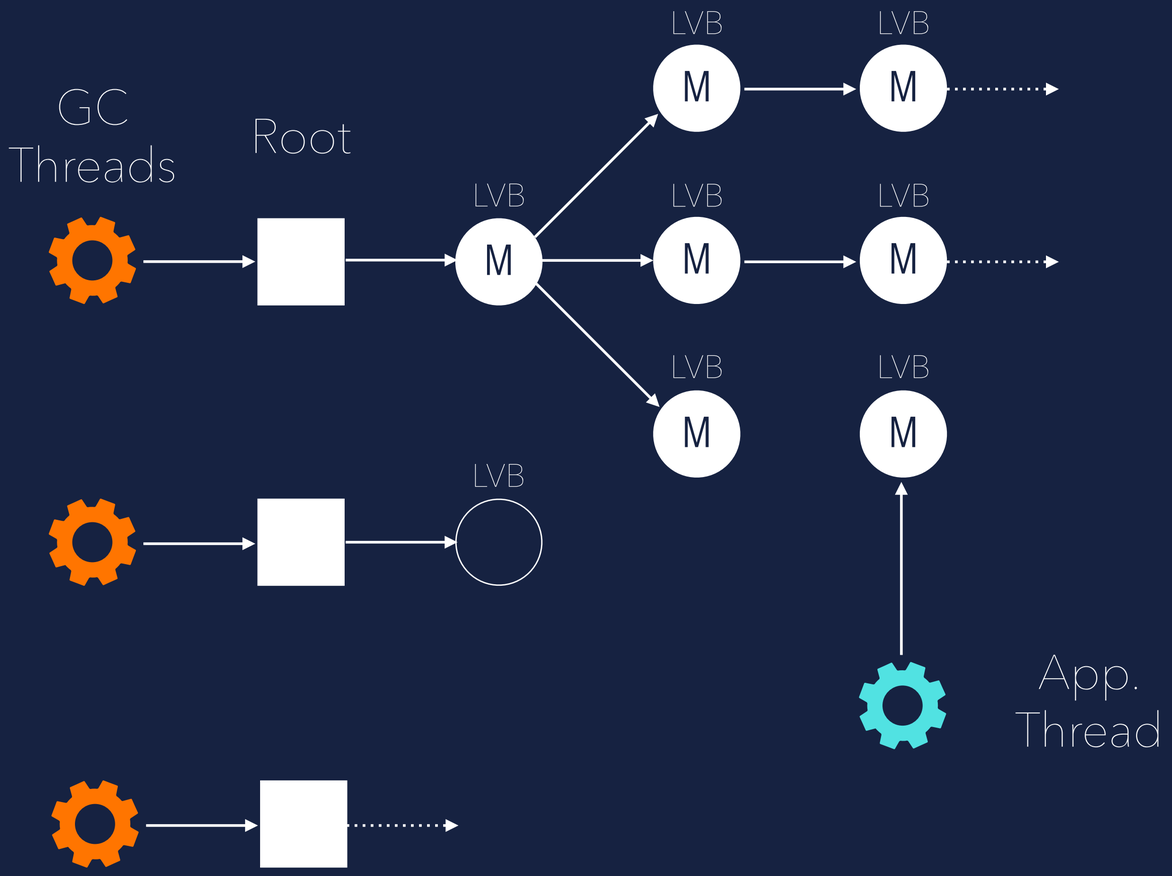
Marking Phase



Test+Jump

C4

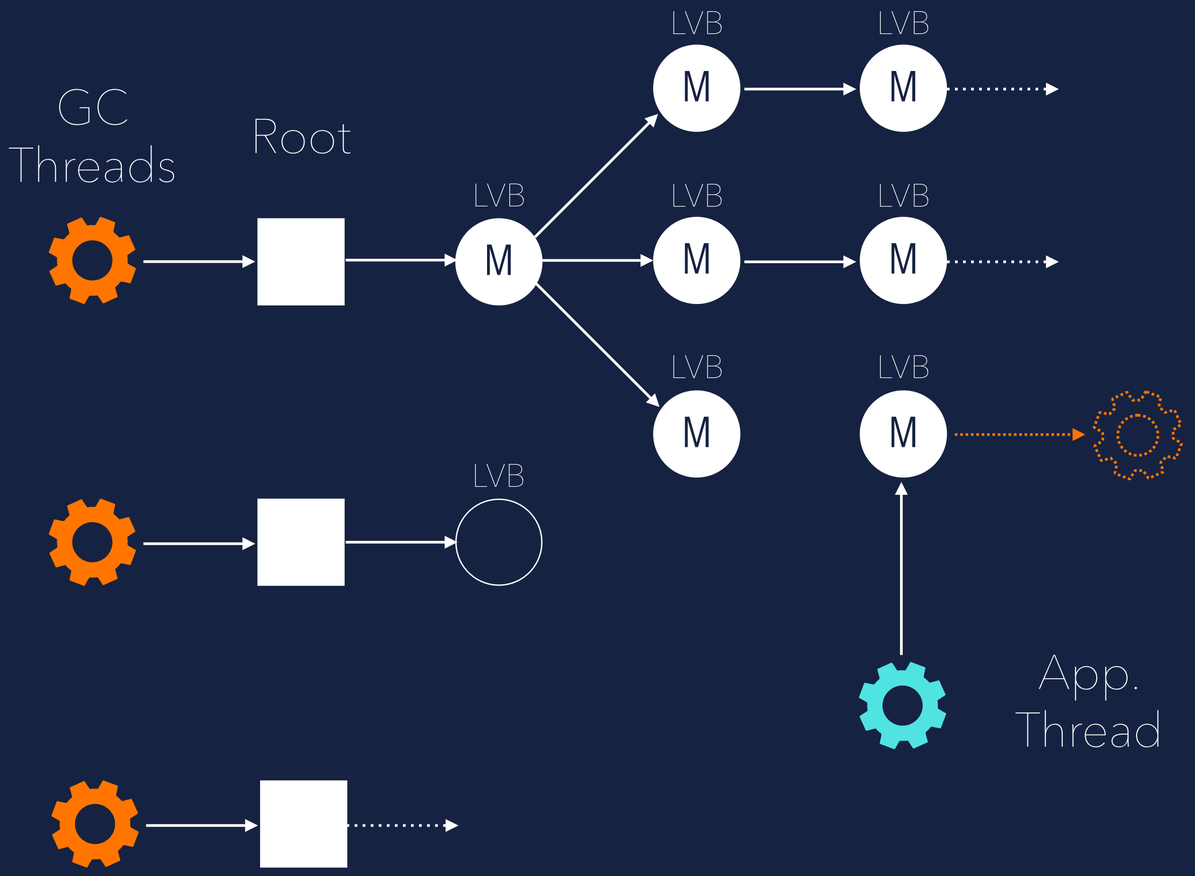
Marking Phase



Mark

C4

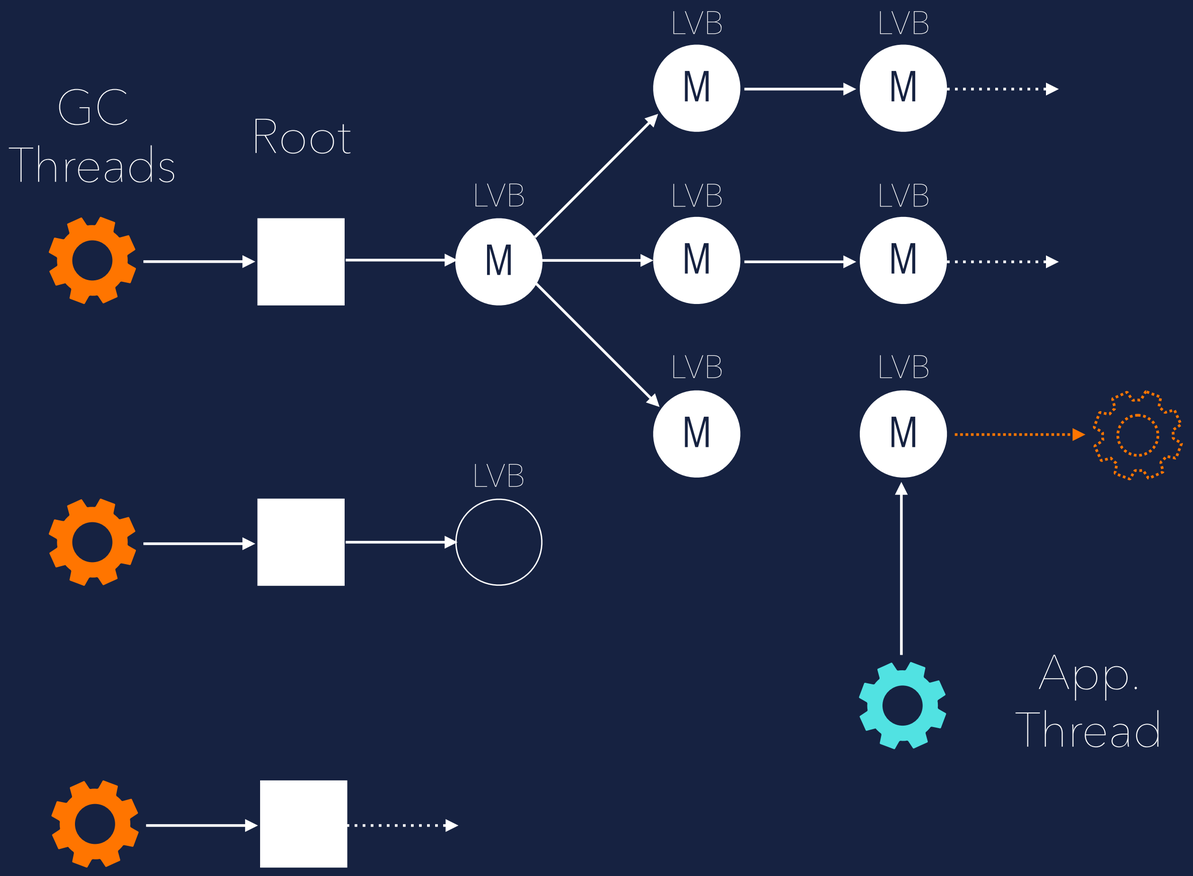
Marking Phase



Hand over
to GC

C4

Marking Phase



No need to mark again by GC !

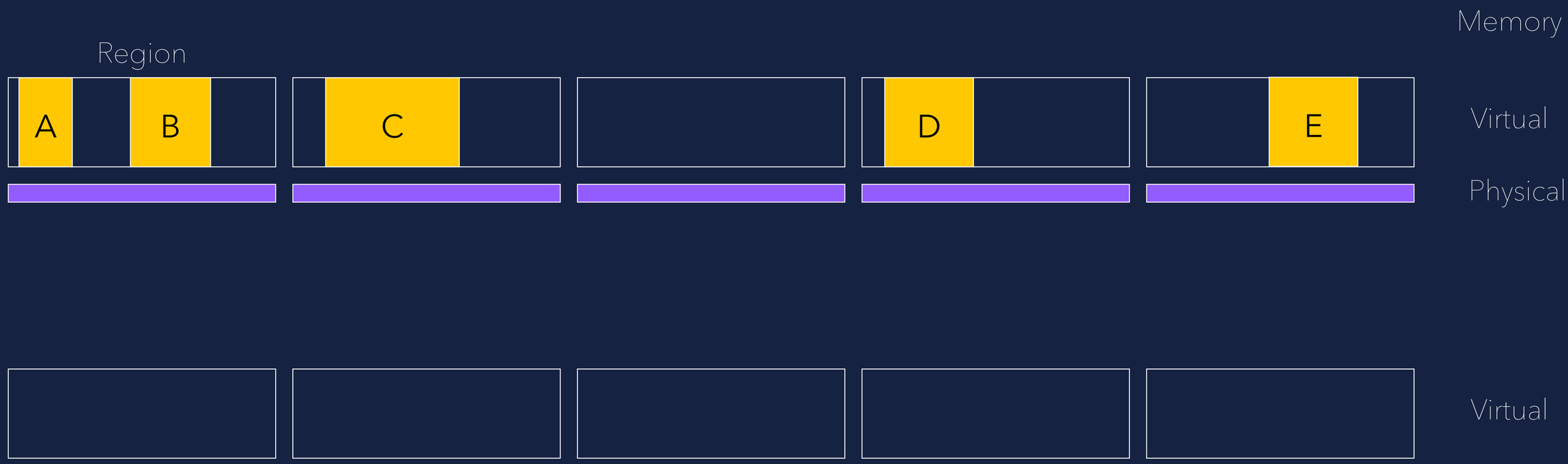
C4

QUICK RELEASE

azul

C4

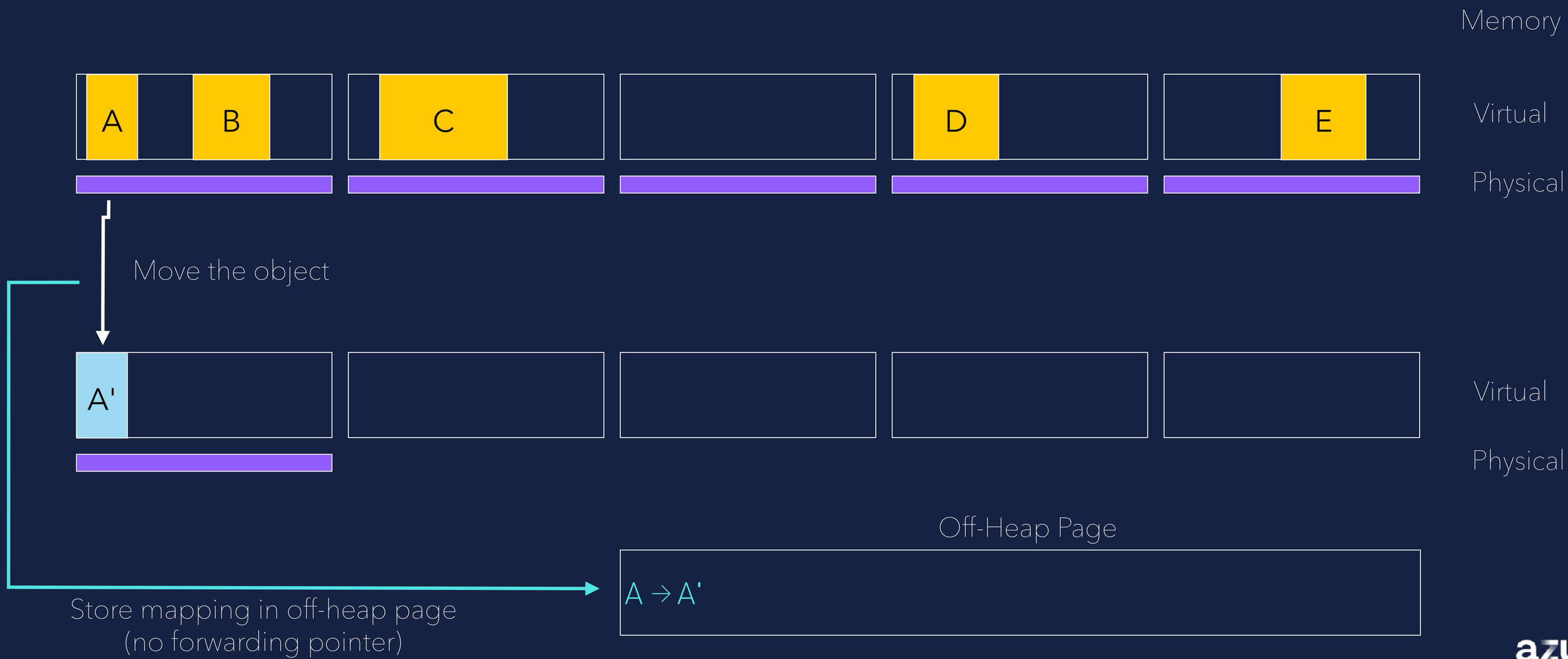
Relocation Phase



azul

C4

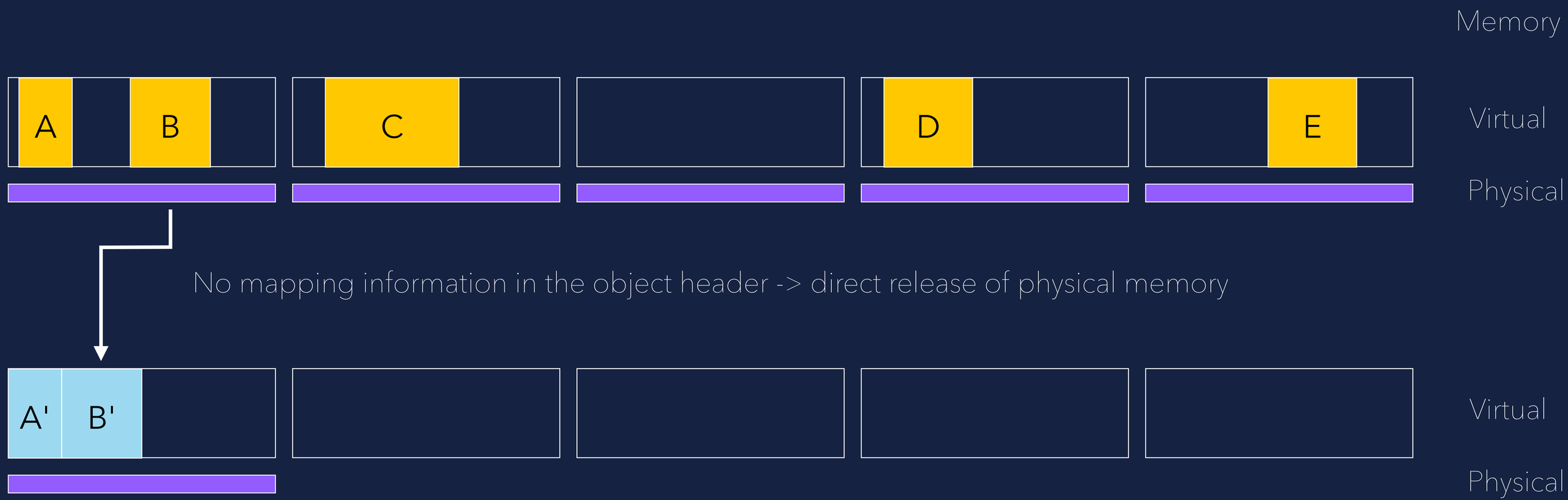
Relocation Phase (Compaction)



azul

C4

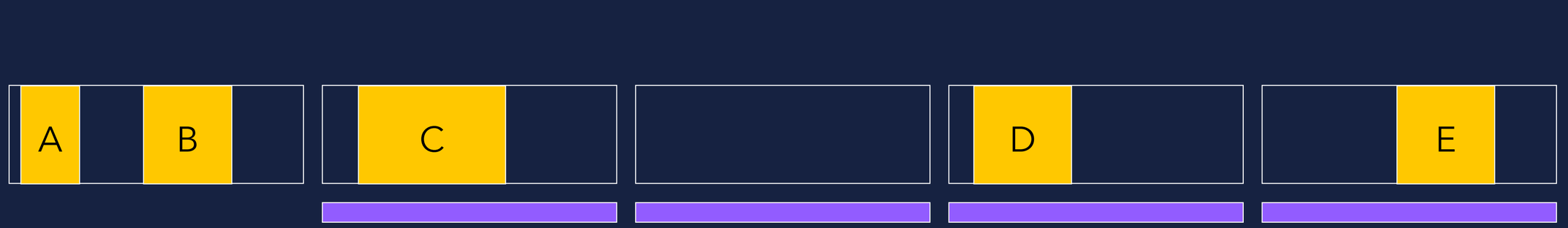
Relocation Phase (Compaction)



azul

C4

Relocation Phase (Compaction)

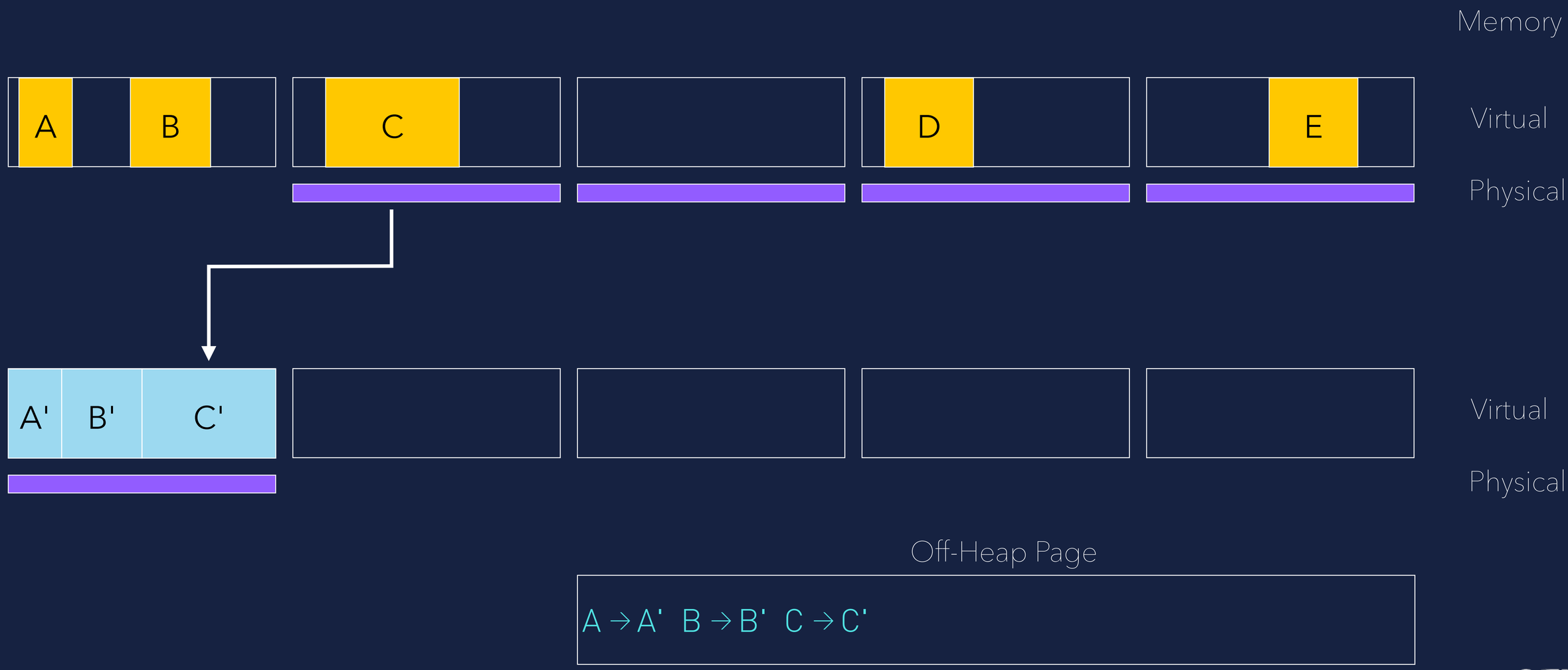


No mapping information in the object header -> direct release of physical memory

azul

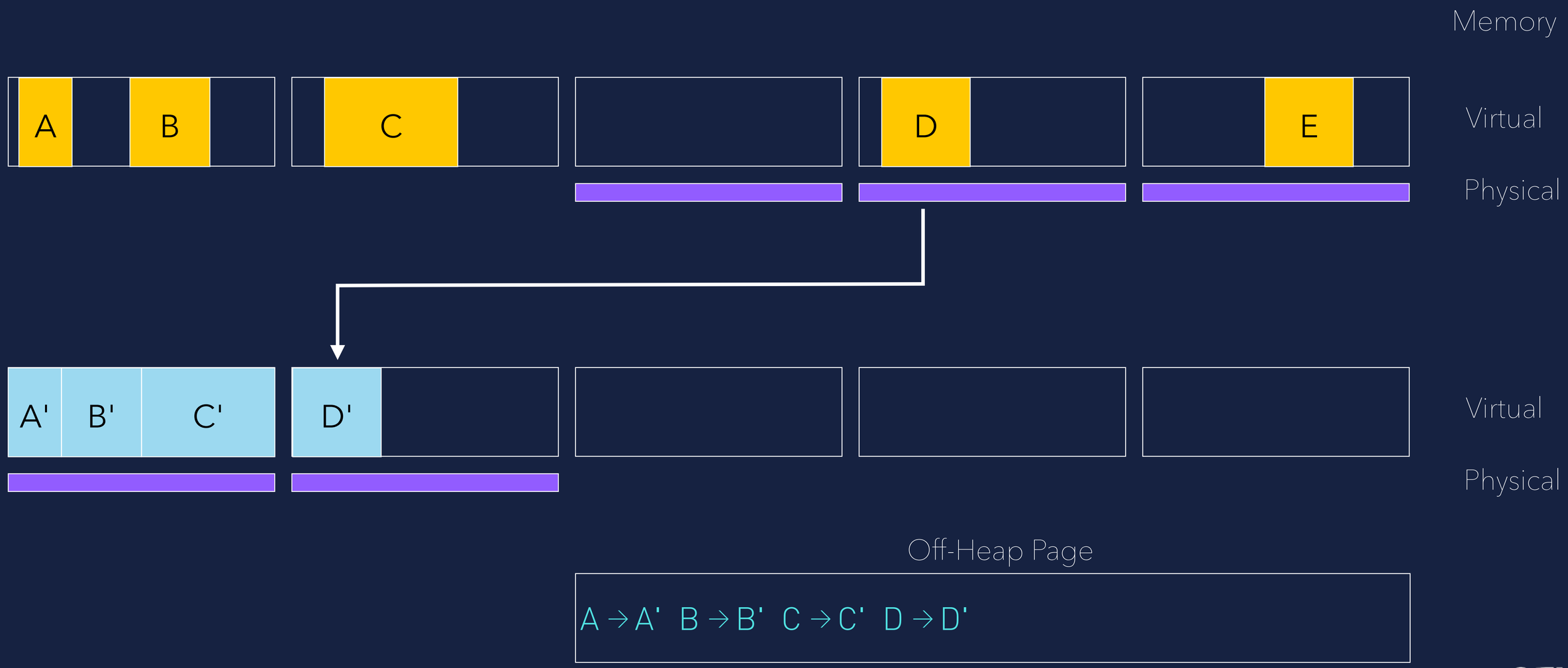
C4

Relocation Phase (Compaction)



C4

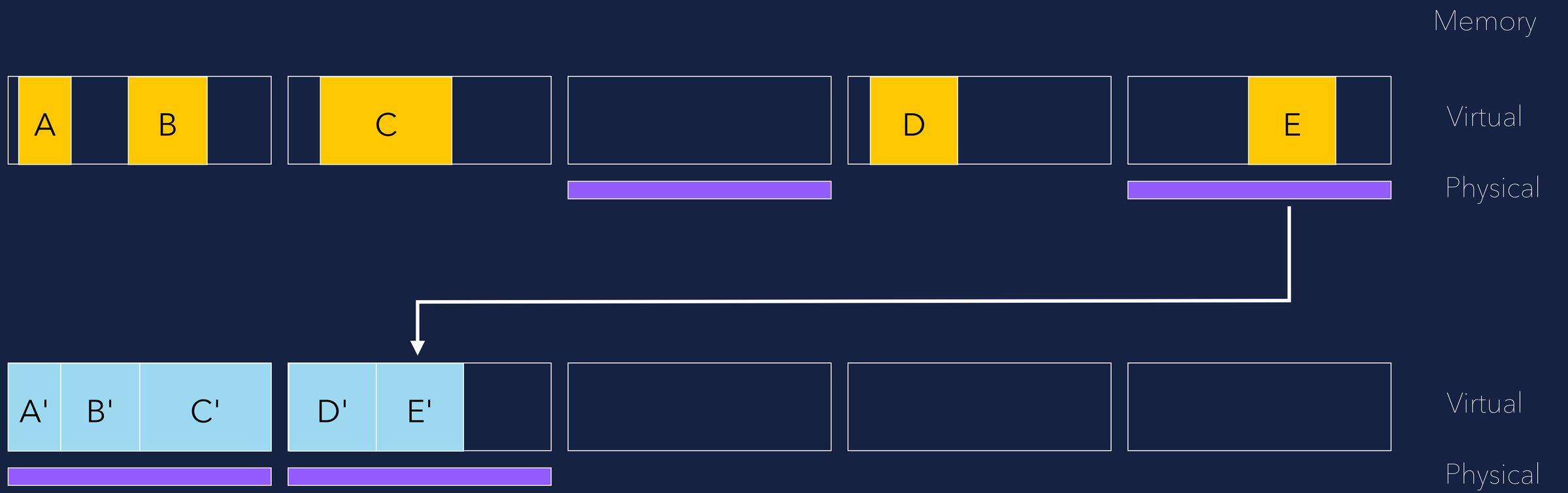
Relocation Phase (Compaction)



azul

C4

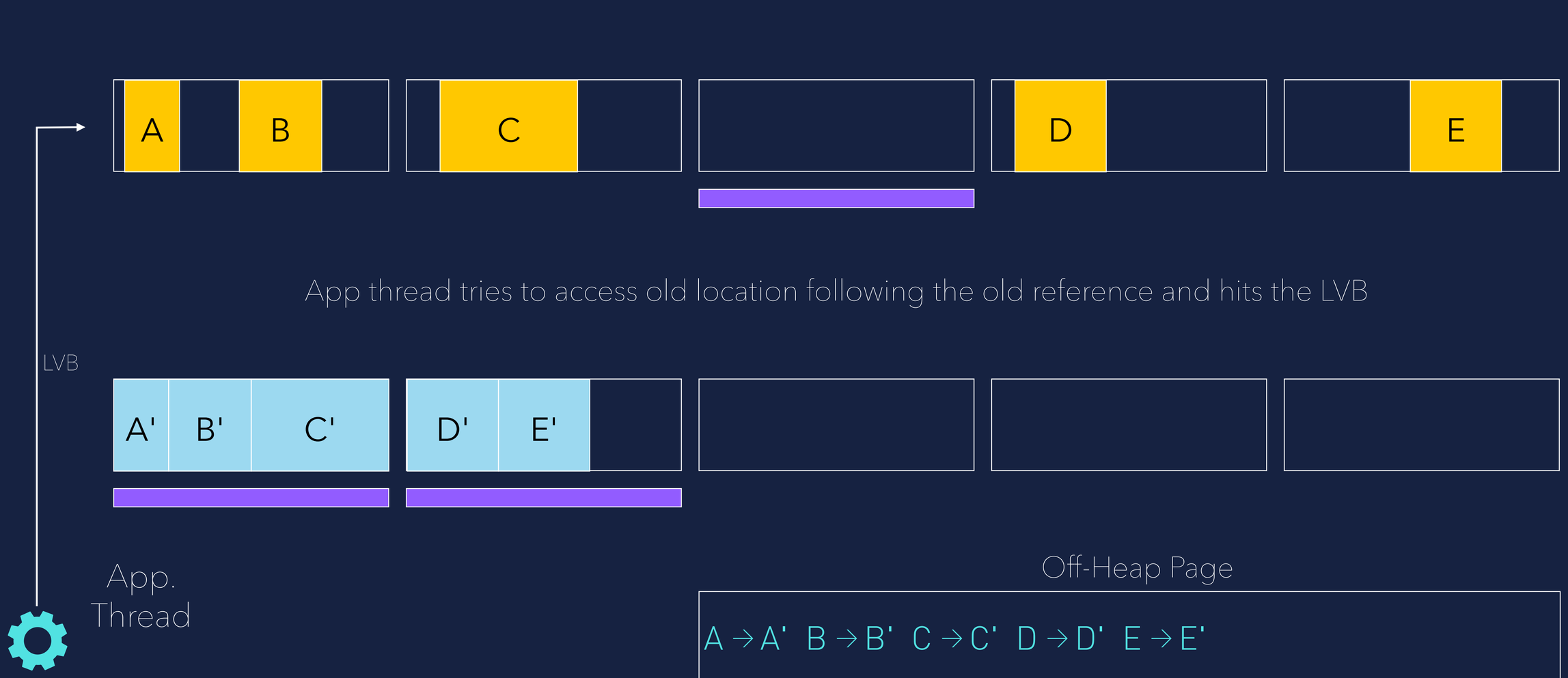
Relocation Phase (Compaction)



azul

C4

Relocation Phase (Quick Release)



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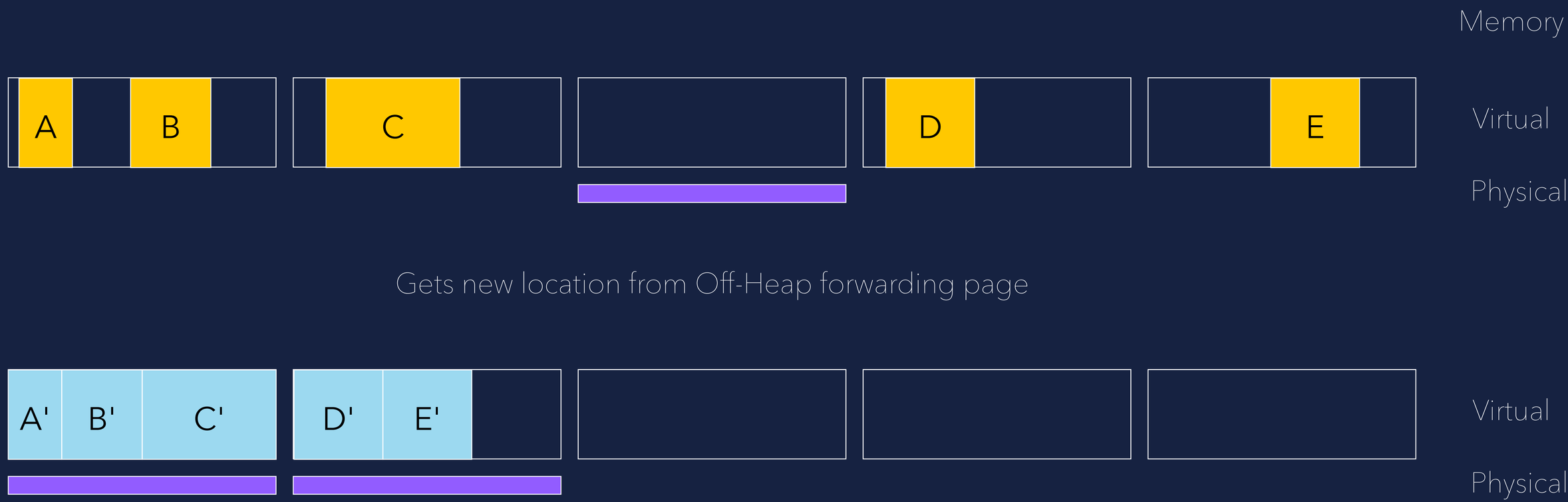
C4

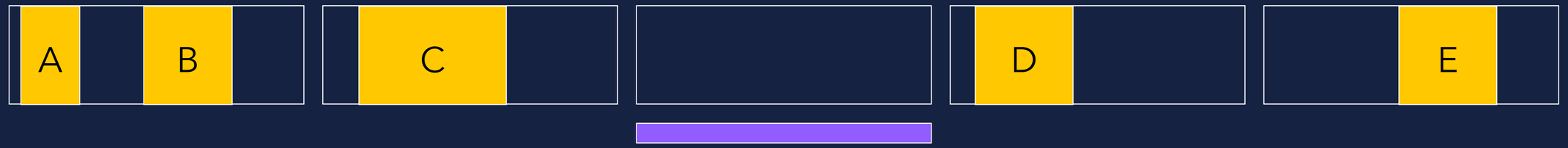
Relocation Phase (Quick Release)



C4

Relocation Phase (Quick Release)

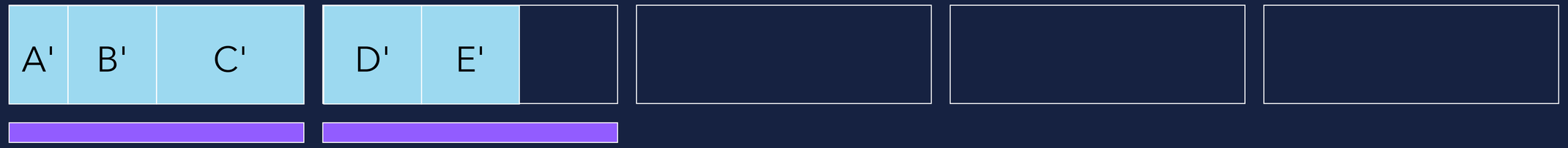
Memory



Virtual

Physical

Updates the reference and can access object at new location



Virtual

Physical

App.
Thread

Off-Heap Page

A → A' B → B' C → C' D → D' E → E'

C4

AVAILABILITY	AZUL ZING JVM
PARALLEL	YES
CONCURRENT	FULLY
GENERATIONAL	YES
HEAP SIZE	LARGE
PAUSE TIMES	SHORT
THROUGHPUT	VERY HIGH
LATENCY	VERY LOW
CPU OVERHEAD	MODERATE (10-20%)

CHOOSE WHEN

- Response time is a high priority
- Using a very large heap (100GB+)
- Predictable response times needed

BEST SUITED FOR

- Low latency sensitive applications
- Large scale systems
- Highly concurrent applications

OS SUPPORT	
JVM SWITCH	> –

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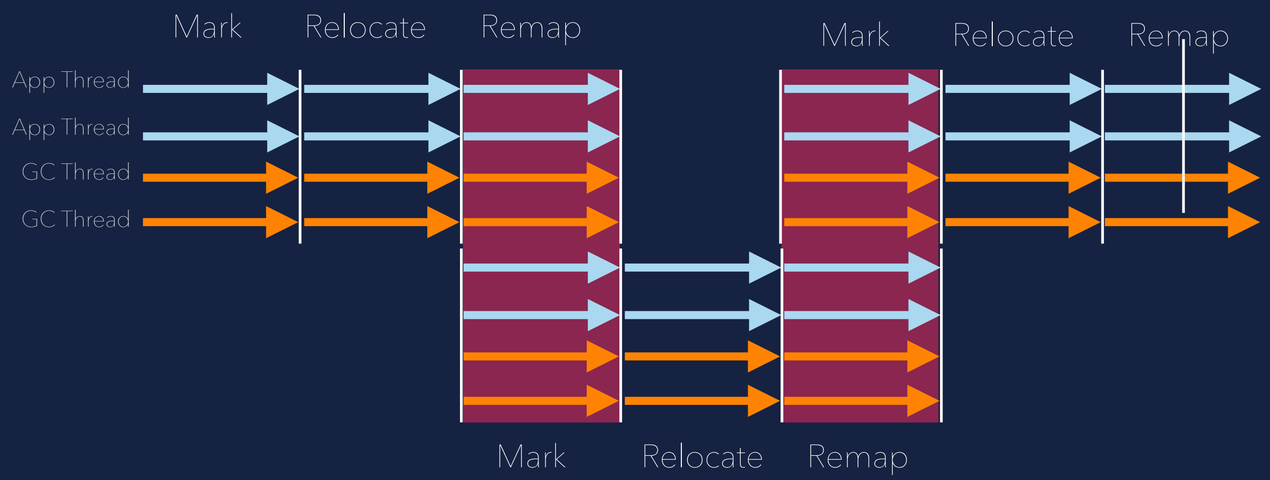
C4

NOTES

- Only available in Azul Zing JVM
- No performance overhead because of faster Falcon compiler



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WHICH ONE...?

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Essential Criteria

- Throughput
  - Percentage of total time spent in application vs. memory allocation and garbage collection

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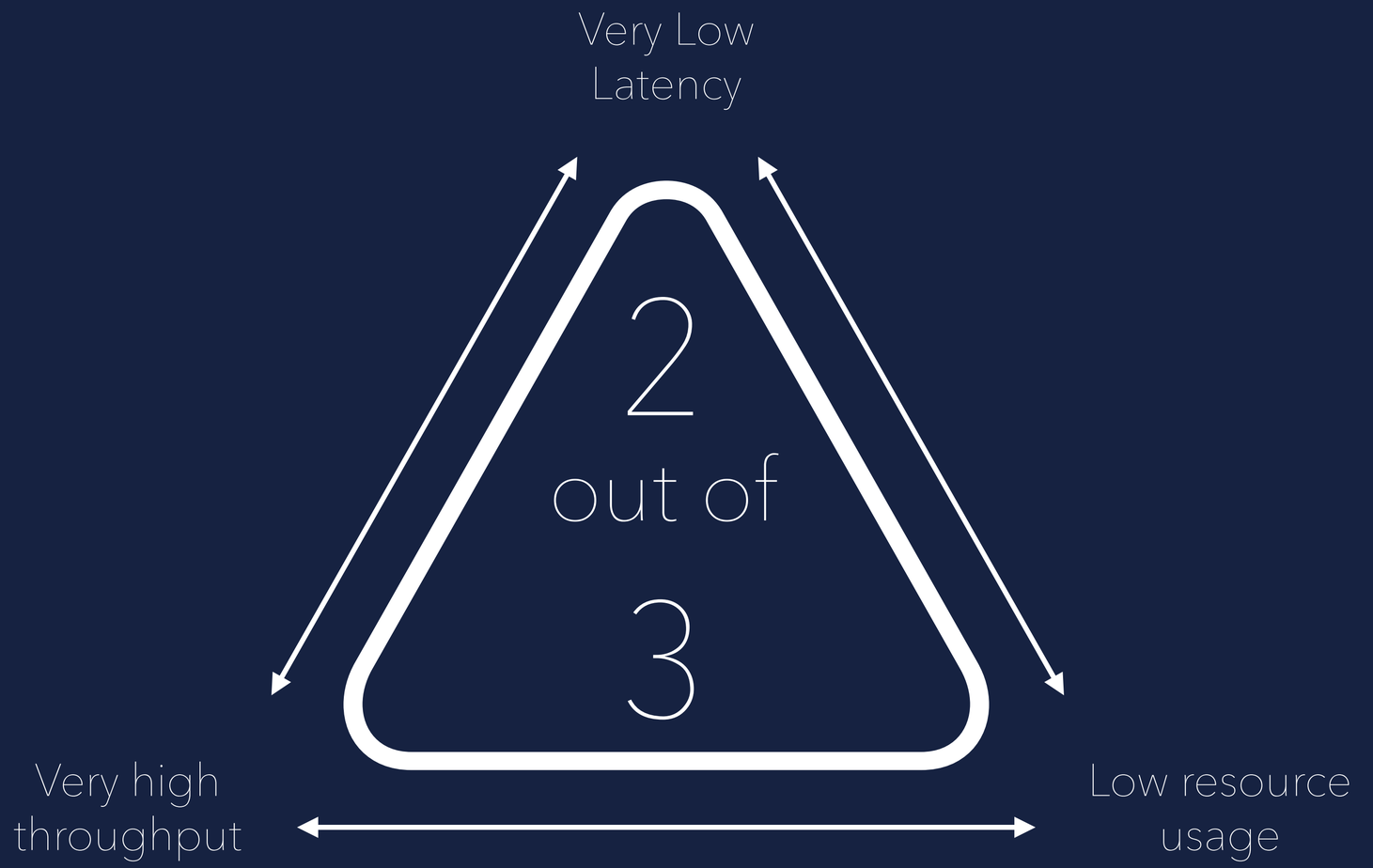
Essential Criteria

- Throughput
  Percentage of total time spent in application vs. memory allocation and garbage collection
- Latency
  Application responsiveness, affected by gc pauses
- Resource usage
  The working set of a process, measured in pages and cache lines

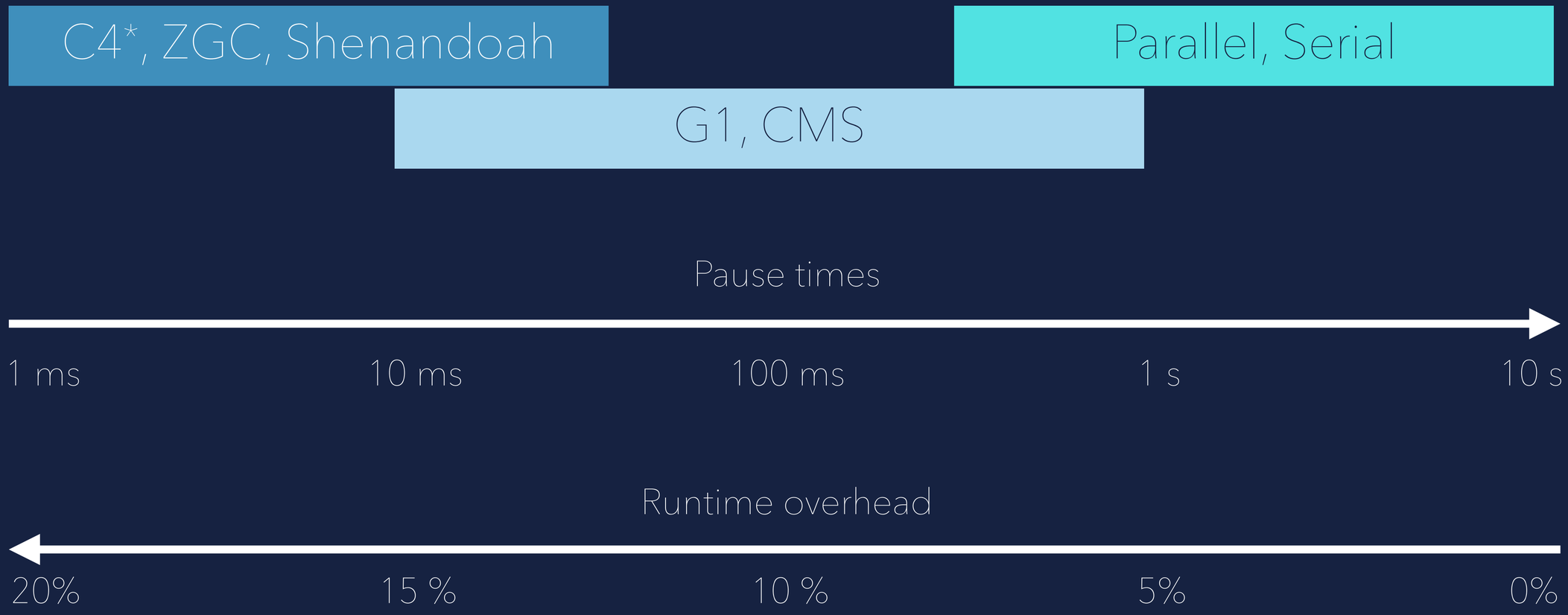
WHICH ONE...?

Essential Criteria



WHICH ONE...?

Choose dependent on your workload



* C4 has less overhead due to faster Falcon compiler

OVERVIEW

OVERVIEW

	Serial GC	Parallel GC	CMS GC	G1	Epsilon	Shenandoah	ZGC	C4
								
Availability	ALL JDK's	ALL JDK's	JDK 1.4-13	JDK 7u4+	JDK 11+	JDK 11.0.9+	JDK15 / 21+	Azul Zing 8+
Parallel	NO	YES	YES	YES		YES	YES	YES
Concurrent	NO	NO	PARTIALLY	PARTIALLY		FULLY	FULLY	FULLY
Generational	YES	YES	YES	YES		NO	NO / YES	YES
Heap Size	SMALL - MEDIUM	MEDIUM - LARGE	MEDIUM - LARGE	MEDIUM - LARGE		LARGE	VERY LARGE	VERY LARGE
Pause Times	LONGER	MODERATE	MODERATE	SHORT - MEDIUM		VERY SHORT (<10ms)	VERY SHORT (<1ms)	VERY SHORT (<1ms)
Throughput	LOW	VERY HIGH	MODERATE	HIGH	VERY HIGH	VERY HIGH	VERY HIGH	VERY HIGH
Latency	HIGHER	LOWER	MODERATE	LOWER		VERY LOW	VERY LOW	VERY LOW
Performance	LOWER	HIGHER	MODERATE	HIGHER	VERY HIGH	VERY HIGH	VERY HIGH	VERY HIGH
CPU Overhead	LOW	LOWER	MODERATE	MODERATE	VERY LOW	LOW - MODERATE	MODERATE - HIGH	MODERATE - HIGH
Tail latency	HIGH	HIGH	HIGH	HIGH		MODERATE	LOW	LOW

TOOLING...

TOOLING

- -Xlog:gc*:/gc-%p-%t.log:tags,uptime,time,level:filecount=10,filesize=128m
  Output of garbage collection details to log file

- jstat
  Tool that provides info on performance and resource consumption of running applications

TOOLING

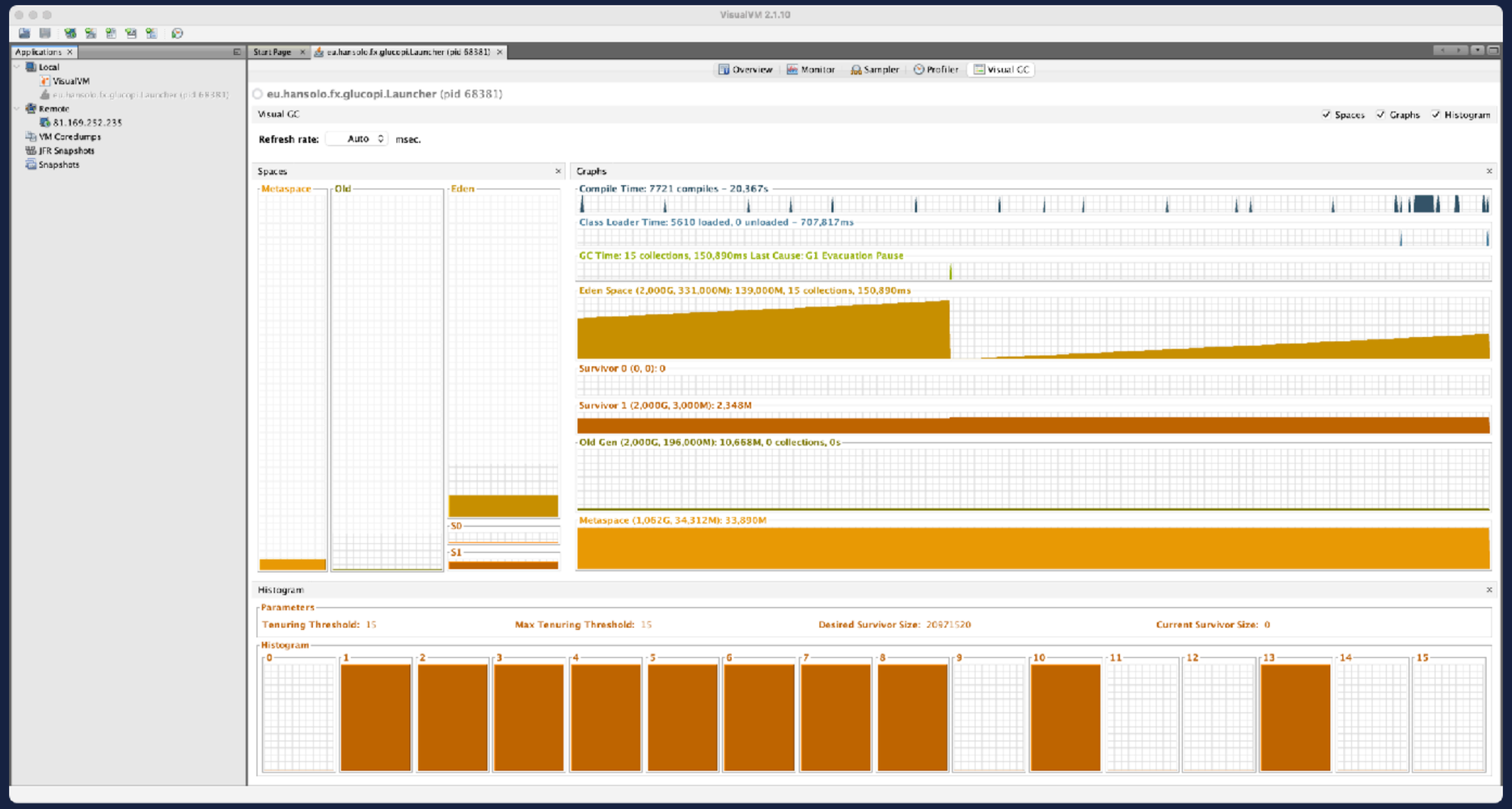
- JITWatch
  A tool for understanding the JVM JIT (https://github.com/AdoptOpenJDK/jitwatch/wiki)
- jHiccup
  A non intrusive tool to monitor platform "hiccups" incl. JVM stalls (https://github.com/giltene/jHiccup)
- VisualVM
  All in one Java troubleshooting tool (https://visualvm.github.io/)

- GCeasy
  Universal GC Log Analyzer (https://gceasy.io)
- JProfiler
  All in one Java profiler (https://www.ej-technologies.com/jprofiler)
- YourKit Java Profiler
  CPU and Java profiler (https://www.yourkit.com/features/)

$

TOOLING

VisualVM + VisualGC plugin



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WANNA KNOW MORE ?

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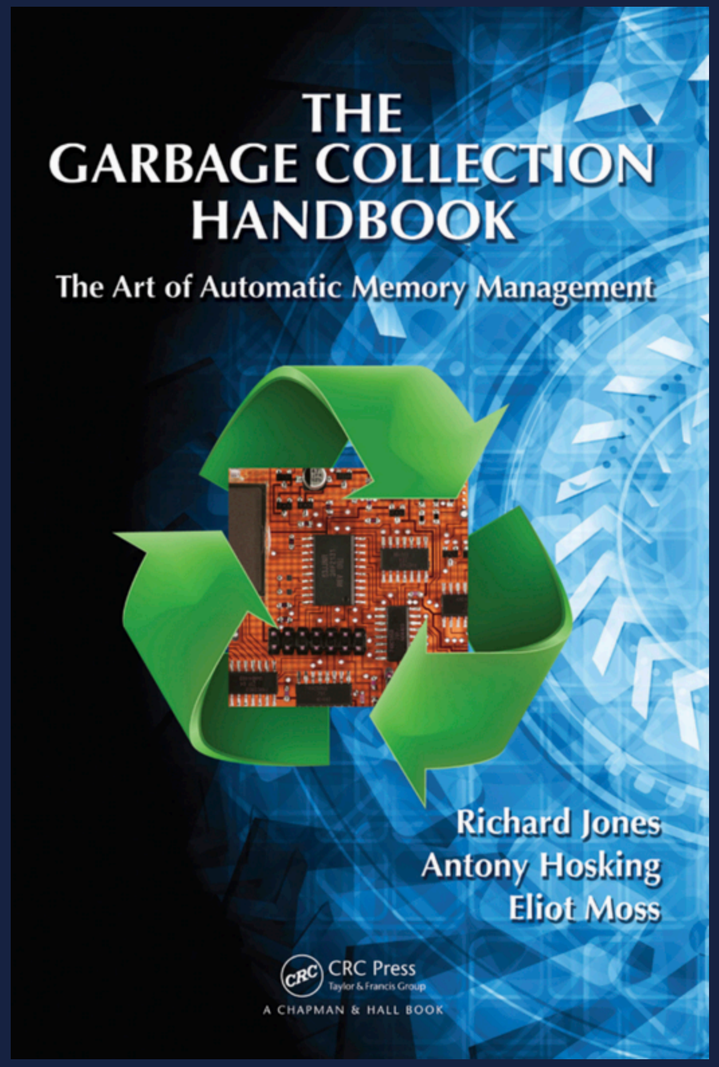
R. Jones et al. "The Garbage Collection Handbook". Chapman & Hall/CRC, 2012



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THANK YOU

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