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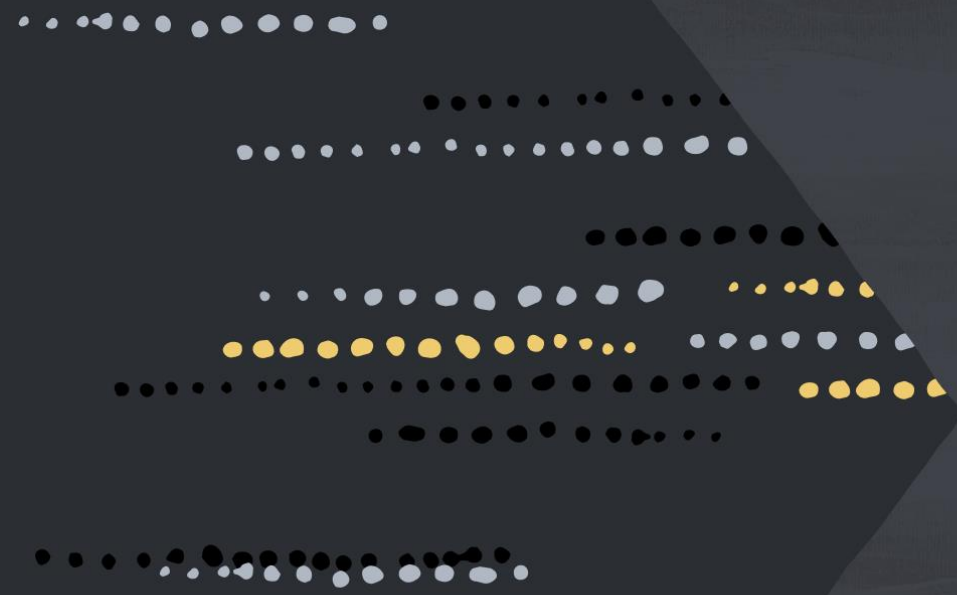
Concurrent thread-stack processing in the Z Garbage Collector



Erik Österlund

Consulting Member of Technical Staff

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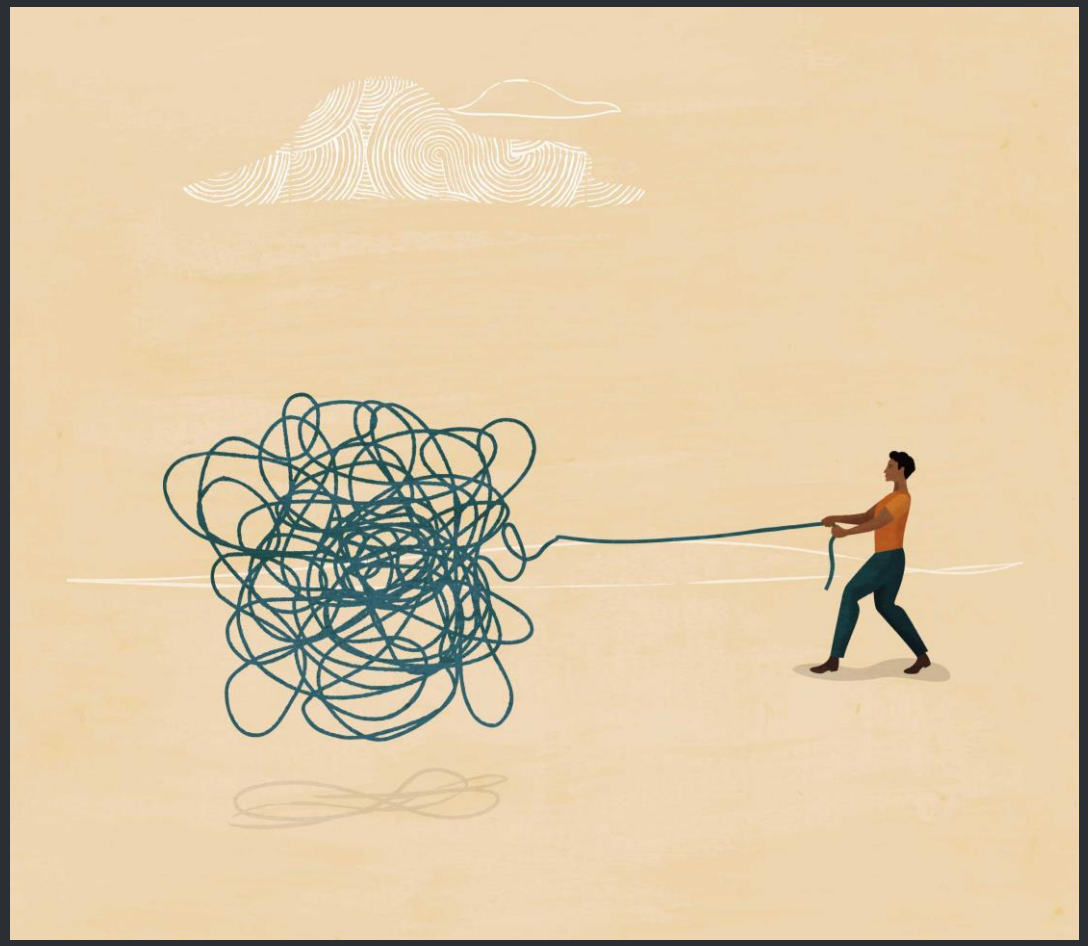


What is ZGC

Low latency

Scalable

Easy to Use

Concurrent
Tracing
Compacting
Region-based
NUMA-aware
Load barriers

Z Garbage Collector Goals

Max GC pause time

10 ms JDK < 16

Max heap size

16 TB

Max CPU overhead

15 %

Easy to Tune!

Z Garbage Collector Goals

Max GC pause time

~~10~~ ms JDK < 16

<1 ms JDK >= 16

Max heap size

16 TB

Max CPU overhead

15 %

Easy to Tune!

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

JDK < 16

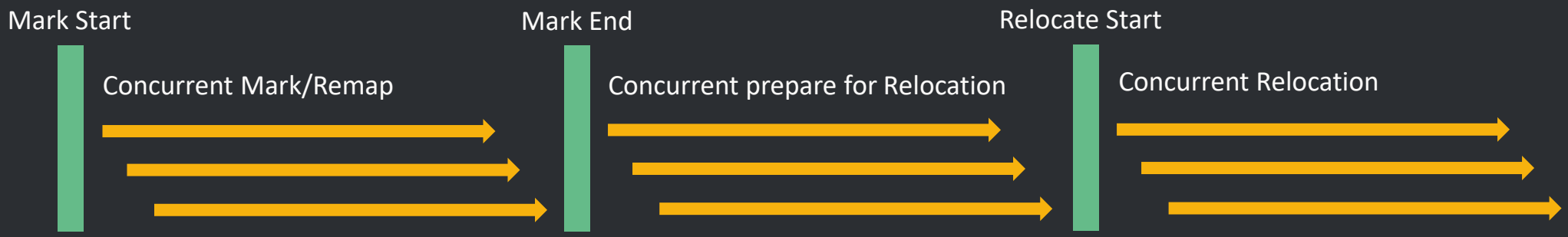
GC pause times **do** increase with the root-set size

JDK >= 16

GC pause times **do not** increase with the root-set size

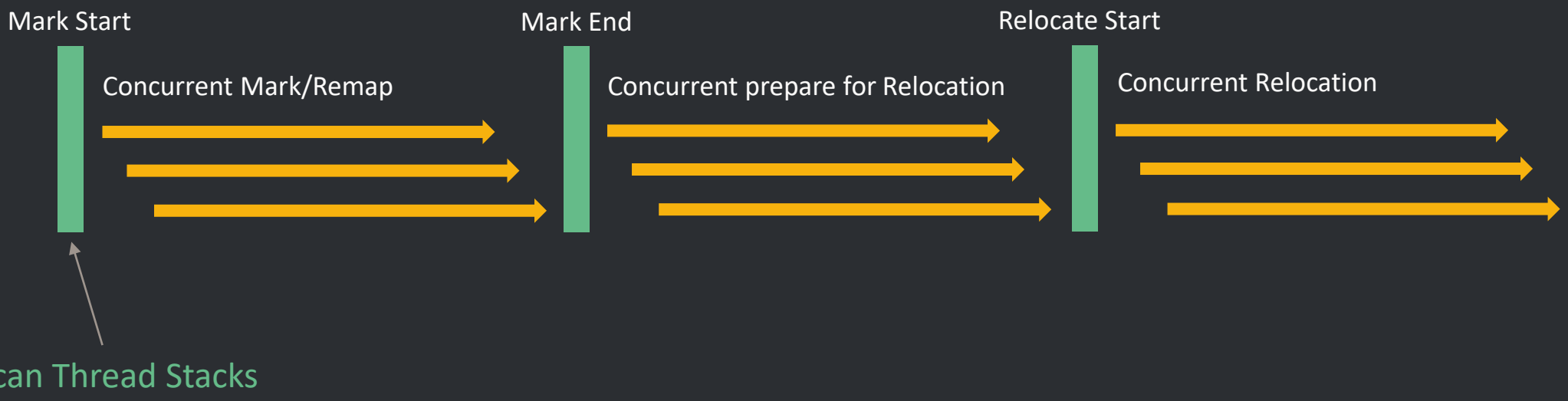
ZGC Phases

JDK < 16



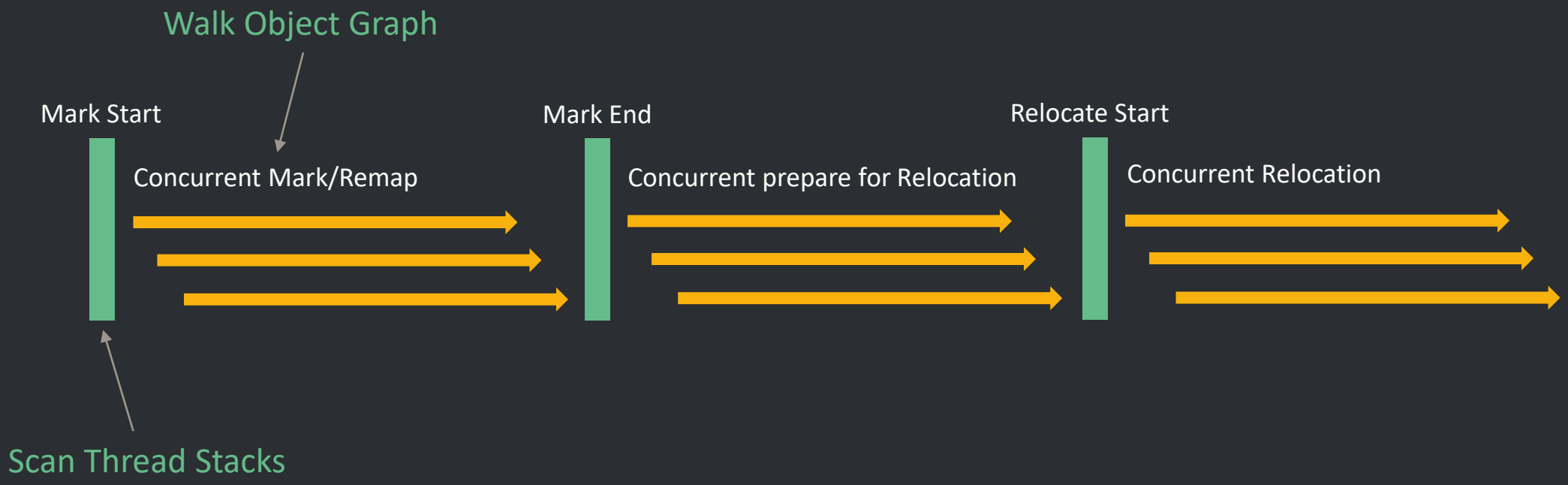
ZGC Phases

JDK < 16



ZGC Phases

JDK < 16



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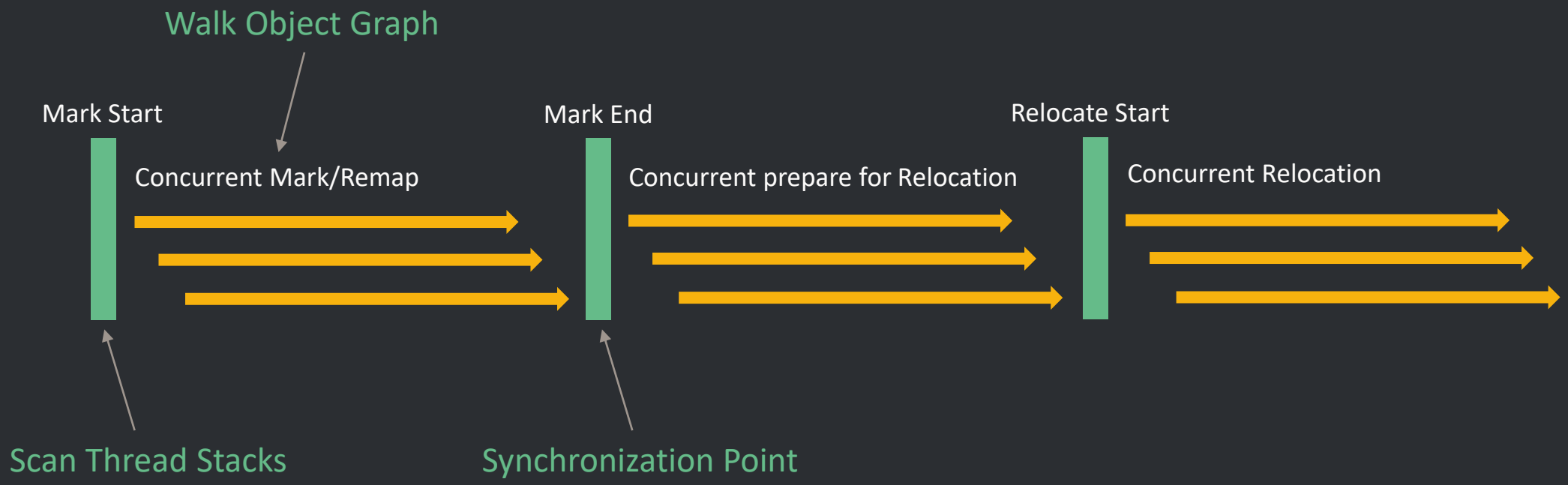
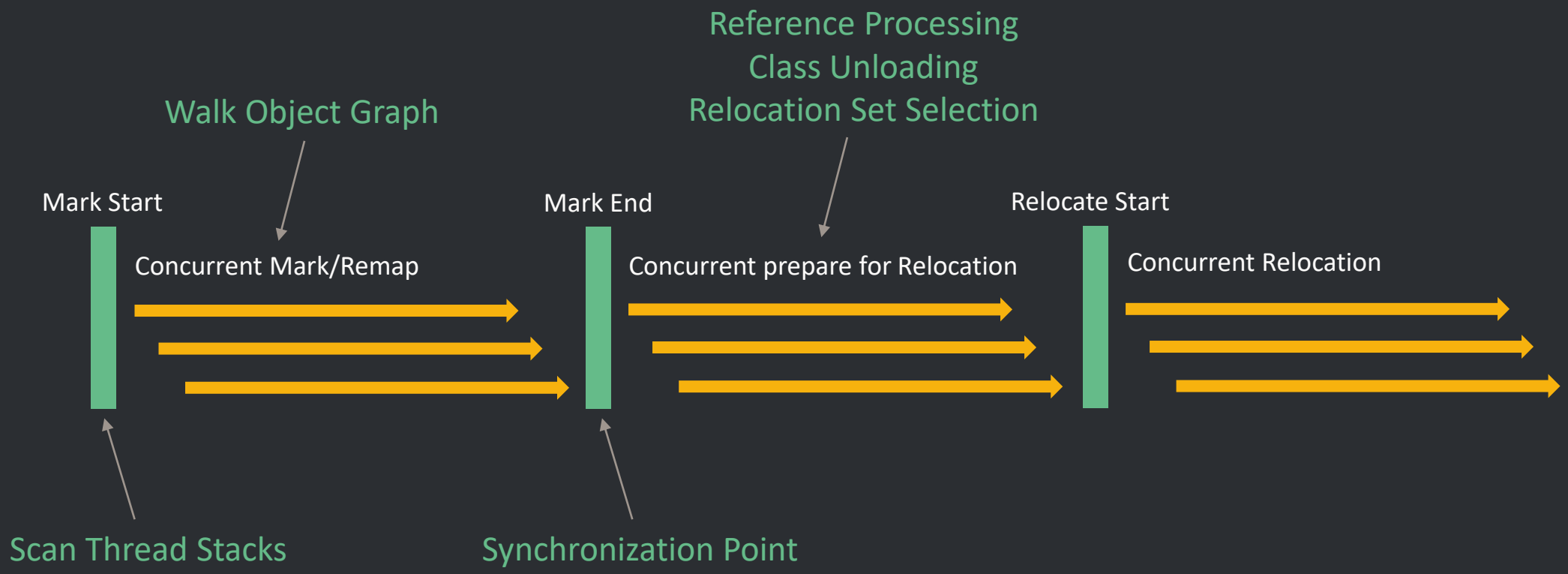


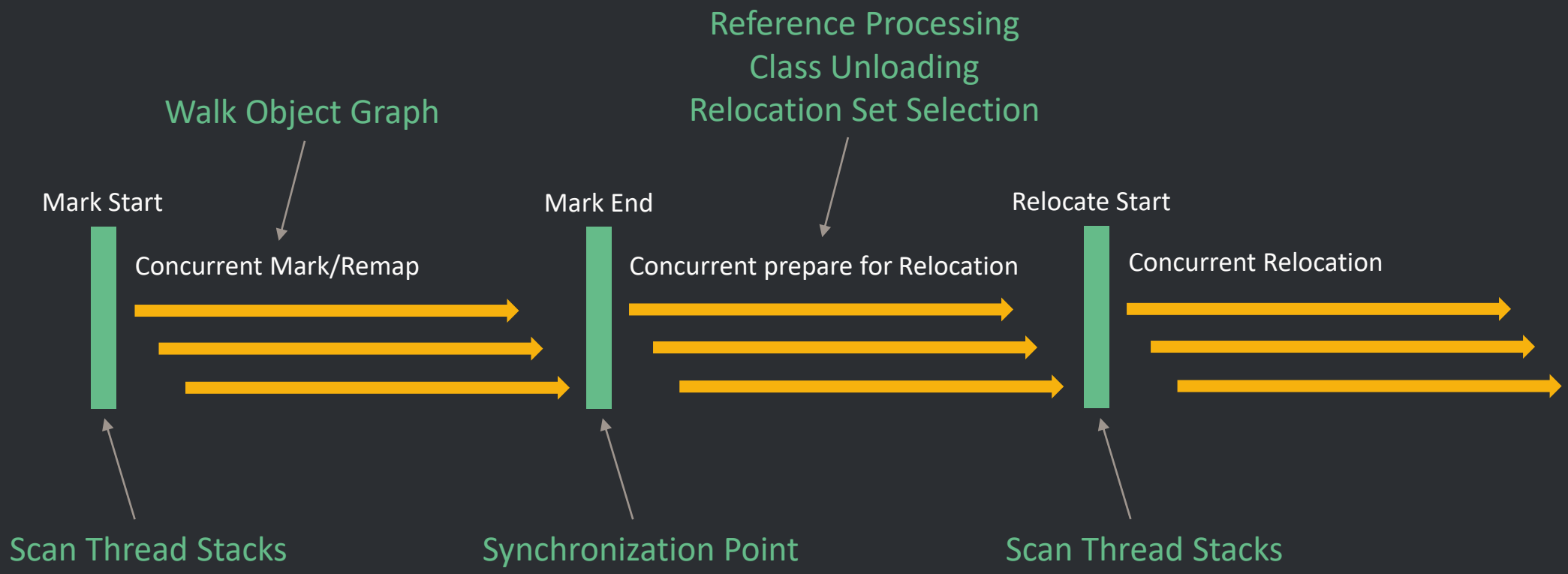
ZGC Phases

JDK < 16



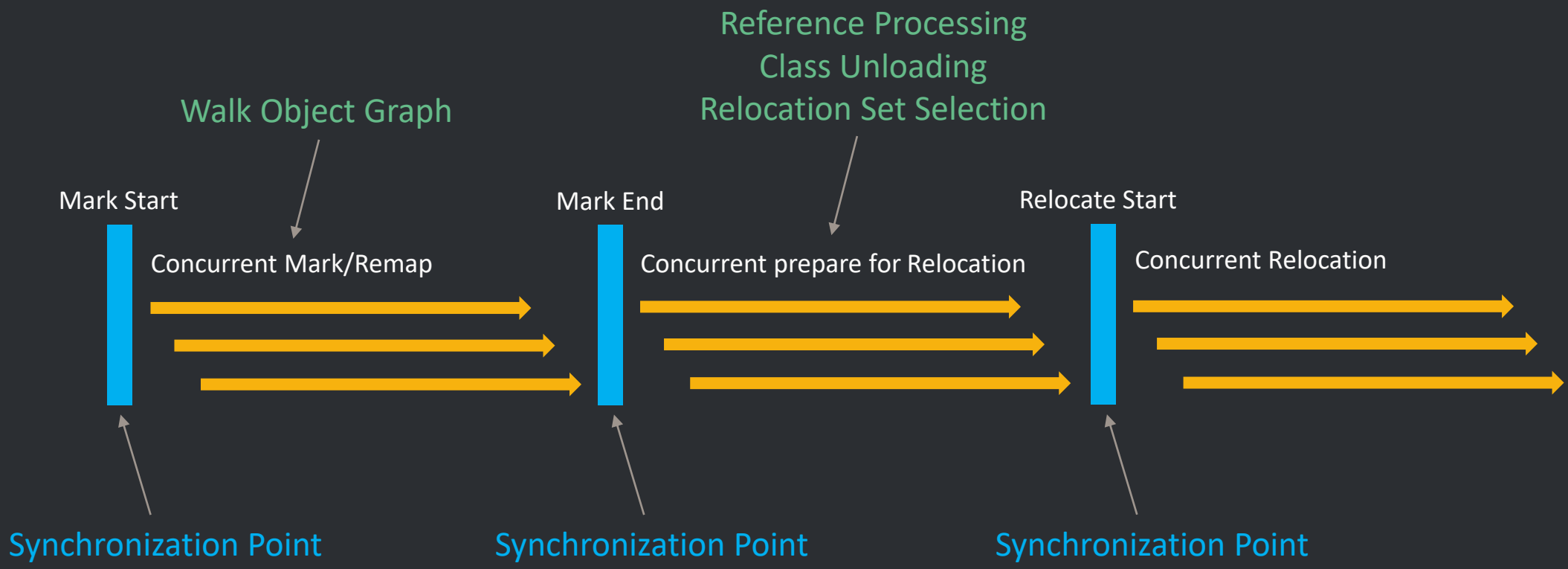
ZGC Phases

JDK < 16



ZGC Phases

JDK >= 16



JEP 376: ZGC: Concurrent Thread-Stack Processing

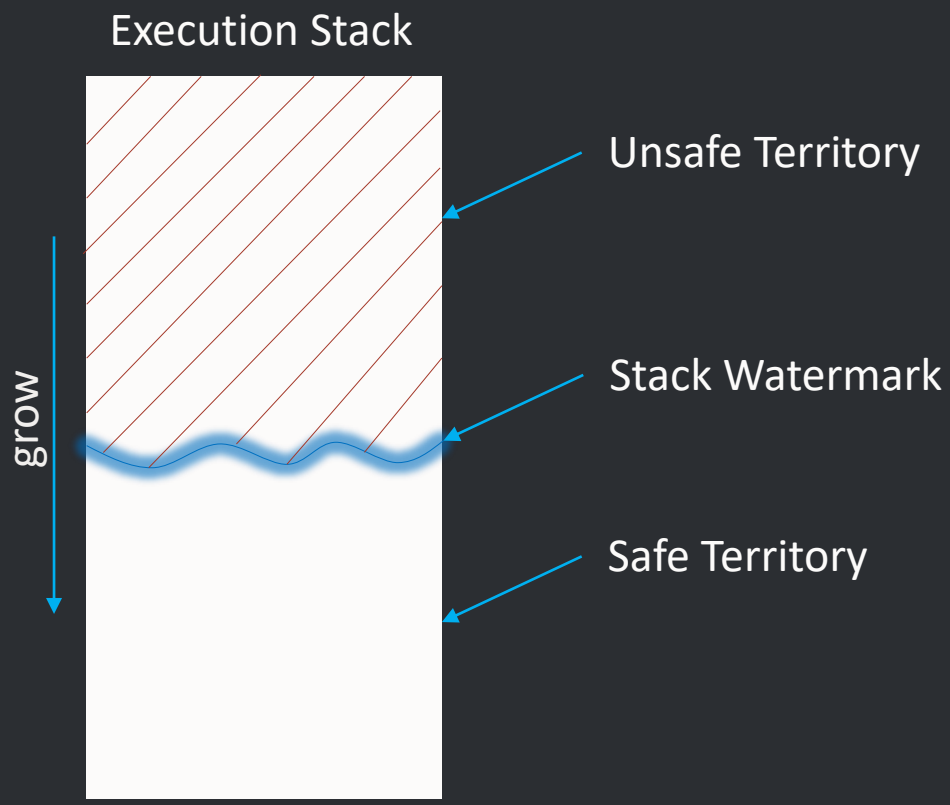
JEP Goals

- Remove thread-stack processing from ZGC safepoints
- Make stack processing lazy, cooperative, concurrent, and incremental
- Remove all other per-thread root processing from ZGC safepoints
- Provide a mechanism by which other HotSpot subsystems can lazily process stacks

Stack Watermarks

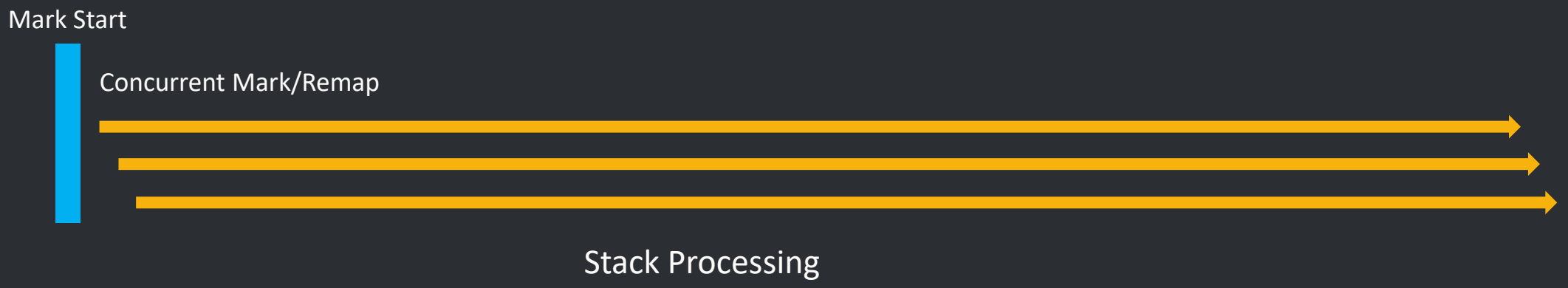
Overview

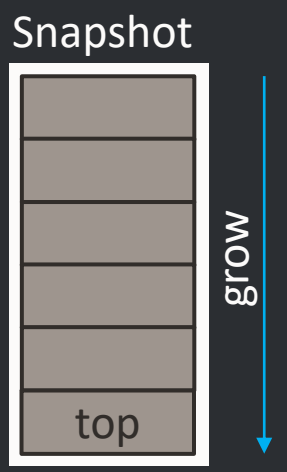
- Need to process object references in stack frames
- Keep track of what frames have been processed
- Ensure that the top 2 frames are always processed
  - Let’s call them “caller” and “callee”
  - Catch violating frame unwinding
  - Process 3 frames when leaving a safepoint
- Use per-thread lock to coordinate processing with GC



Stack Processing Overview

What we want to do





Stack Processing Overview

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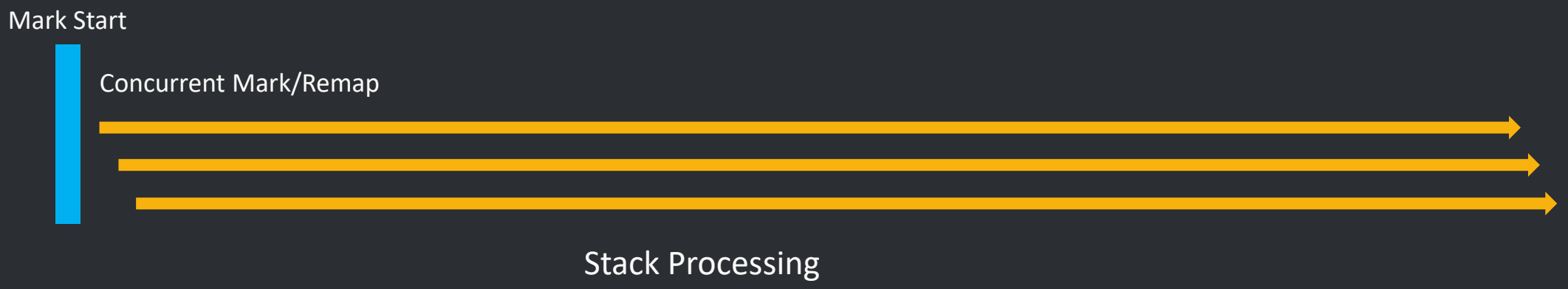

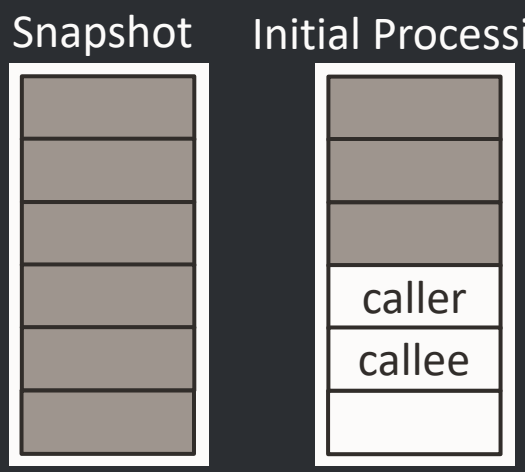

Stack Processing Overview

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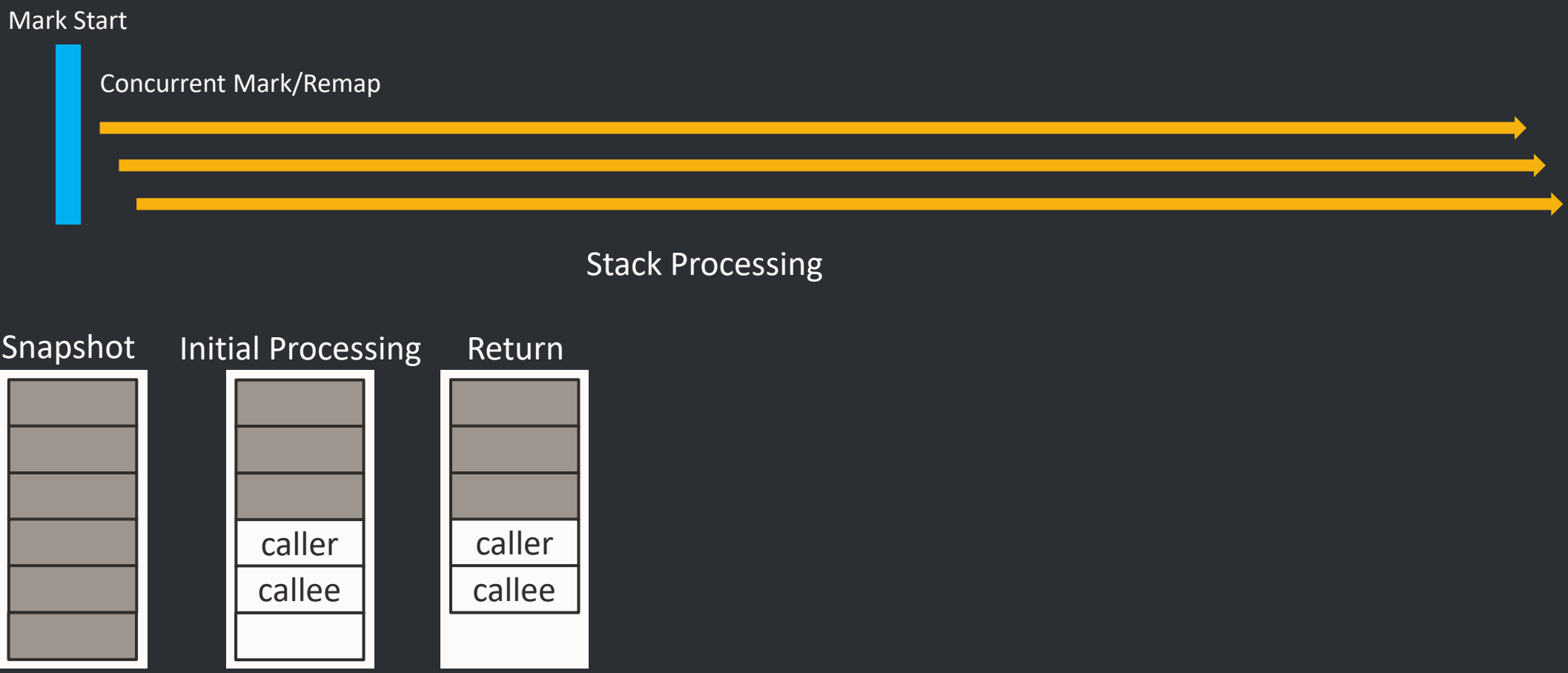
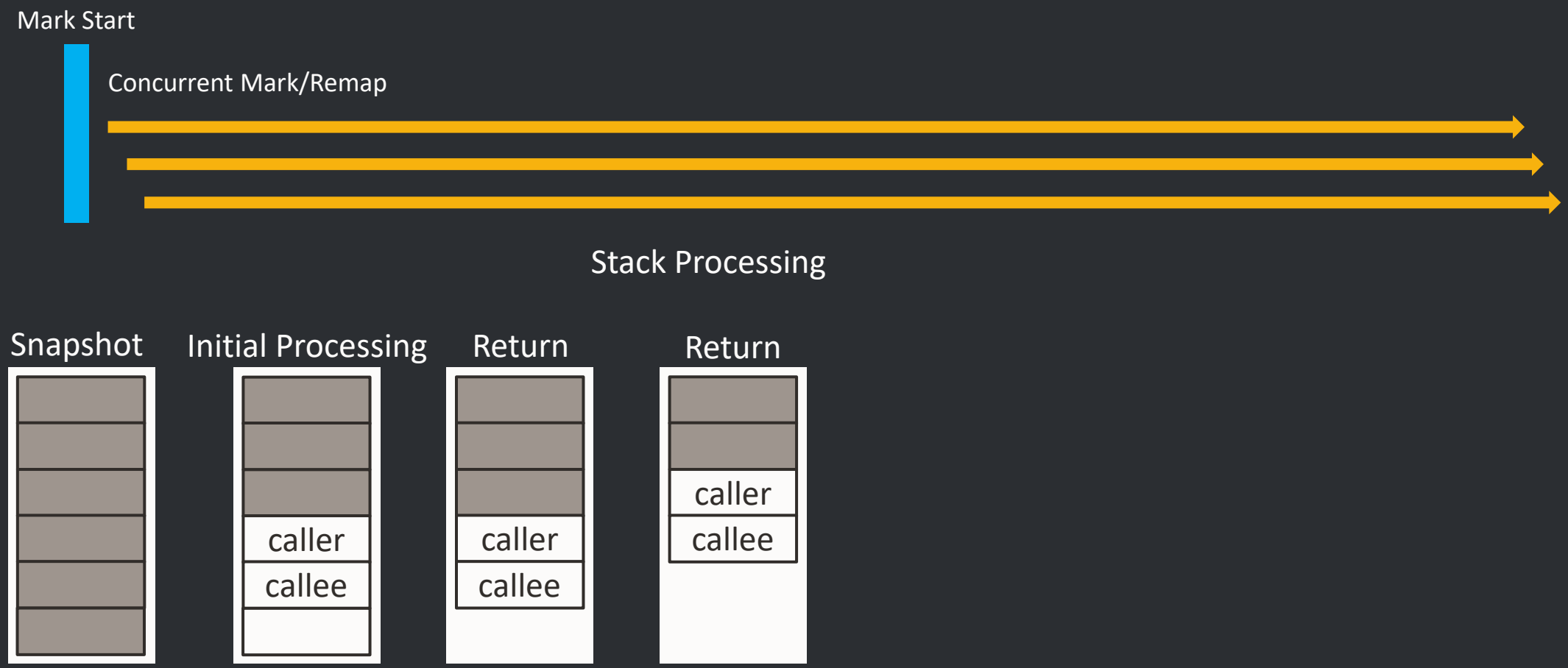


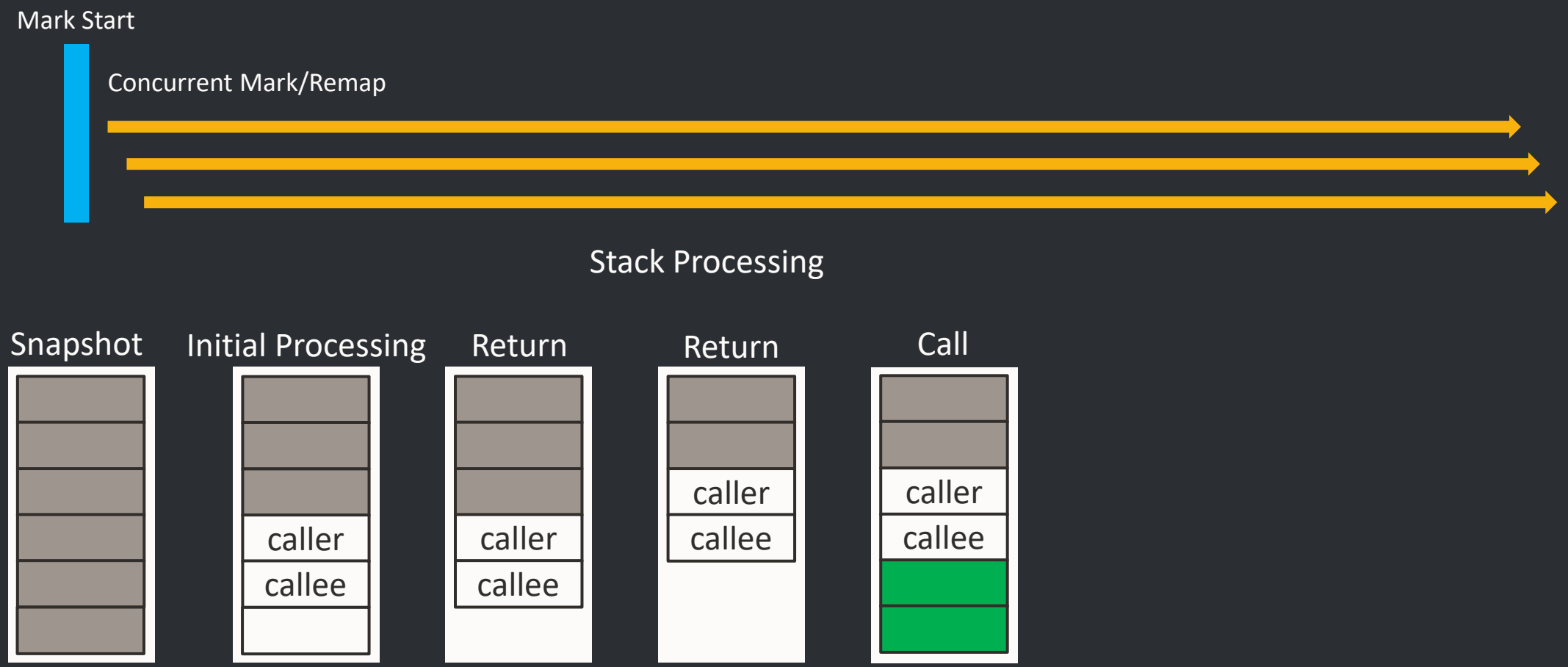
Stack Processing Overview

What we want to do



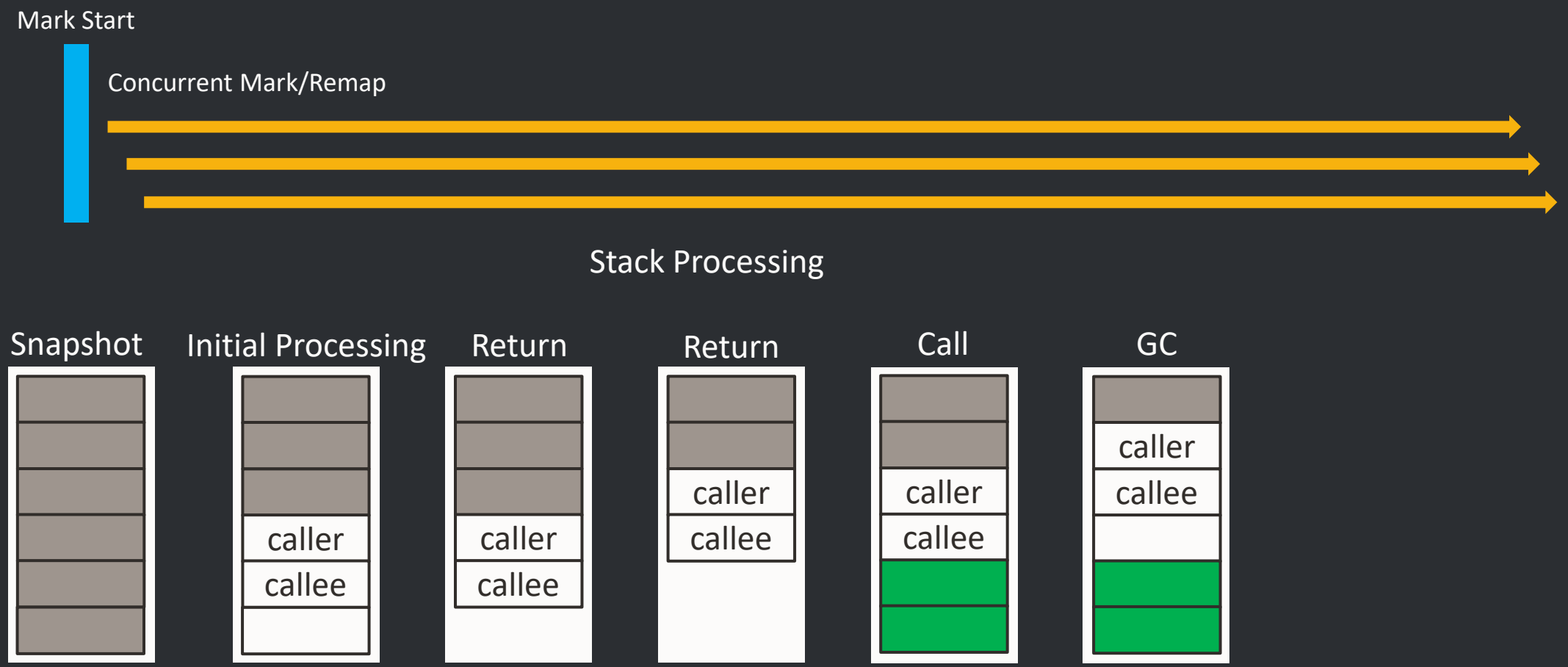
Stack Processing Overview

What we want to do



Stack Processing Overview

What we want to do



Stack Processing Overview

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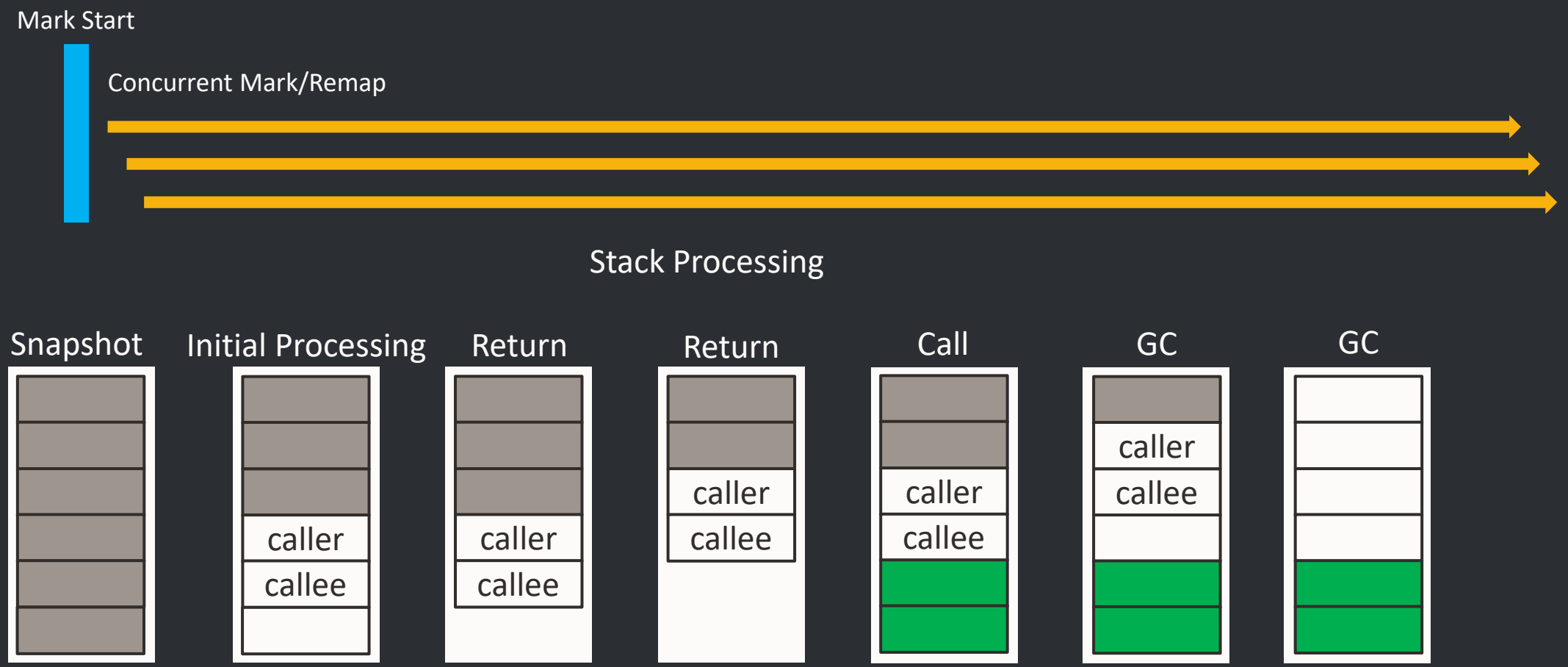


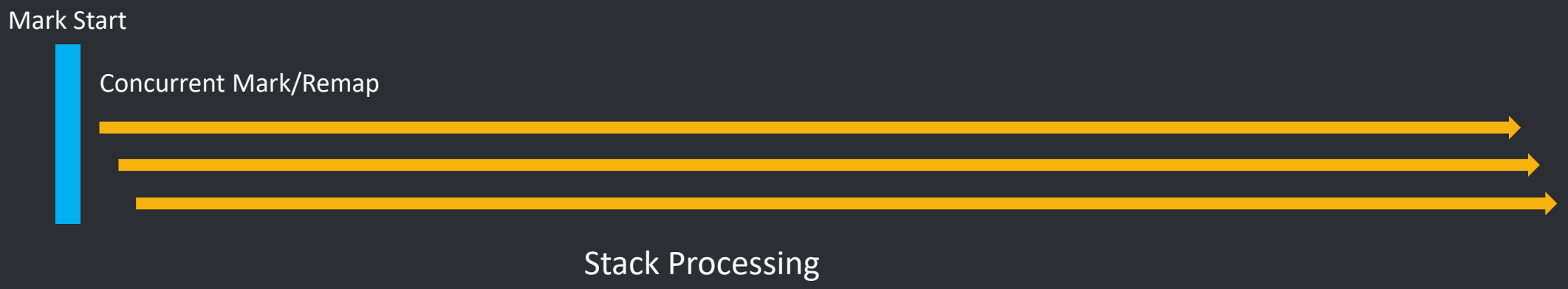
Stack Watermark Barrier

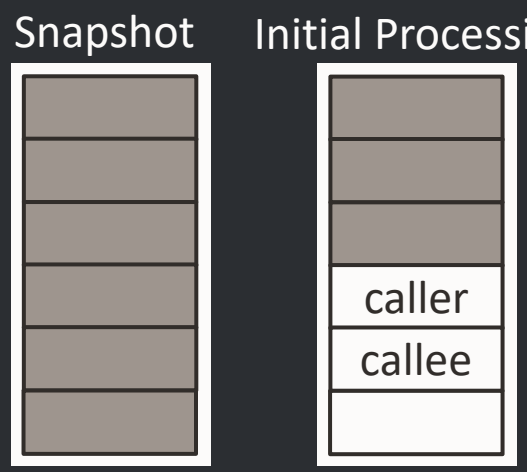
Initial Processing

- At the GC safepoint, we flip the current GC phase, and continue
- When Java thread wakes up from safepoint, it detects the phase change
  - Detects stack and thread roots are invalid
- Trigger initial processing
  - Process three frames
  - Process other thread roots
- Update GC phase of stack watermark

Stack Processing Overview

What we want to do





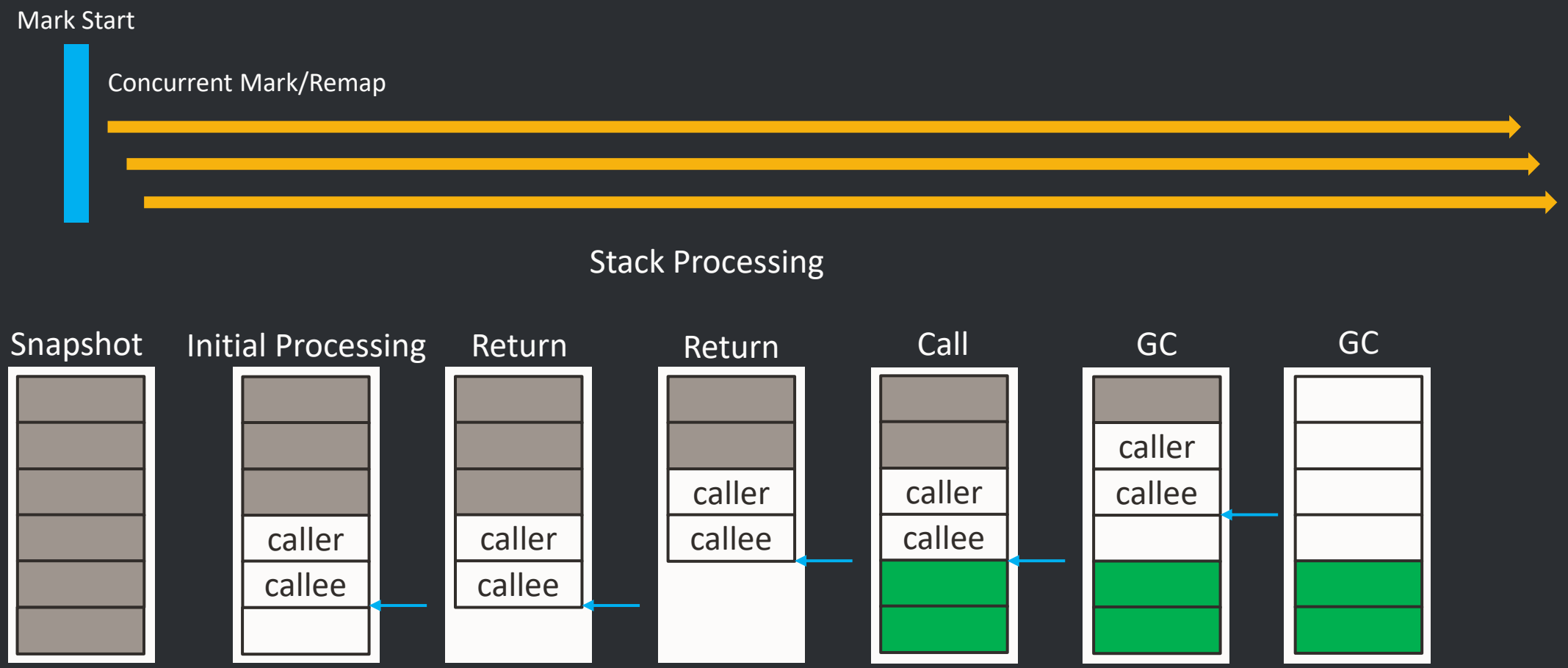
Stack Watermark Barrier

Intercepting dangerous returns

- Before returning, check if stack watermark invariant will break (at least 2 frames processed)
- Compare if frame pointer > thread-local “poll” value
  - Top frame grows and shrinks compared to snapshot, but frame pointer is constant
- Poll value set to stack pointer of “callee” frame

Stack Processing Overview

What we want to do



Stack Watermark Barrier

Intercepting dangerous returns

- Adding instructions per compiled call can be performance sensitive
- Ideal to incorporate check into existing checks
- Stack watermark barrier replaces previous method epilog safepoint poll

Compiled Method Epilog

Overview

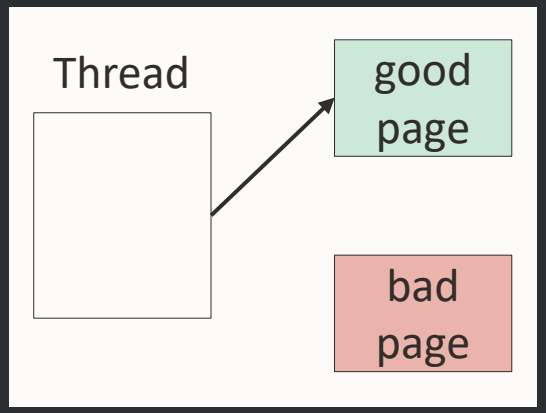
- Frame pointer is ***not*** available
- Poll happens after unwinding frame
- Stack pointer available instead
  - Frame pointer - 8

Compiled Method Epilog

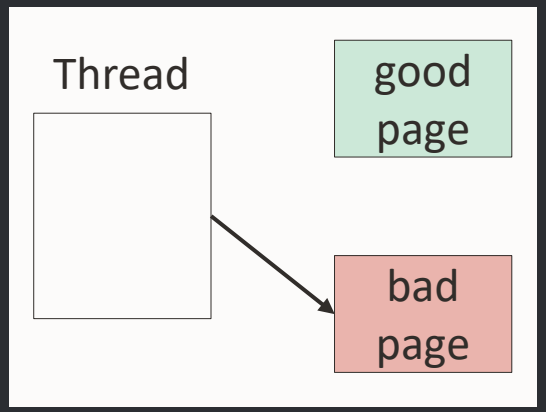
x86_64 assembly

```
movq rtmp, 0x330(r15)
testb rax, 0x0(rtmp)
```

No pending safepoint



Pending safepoint

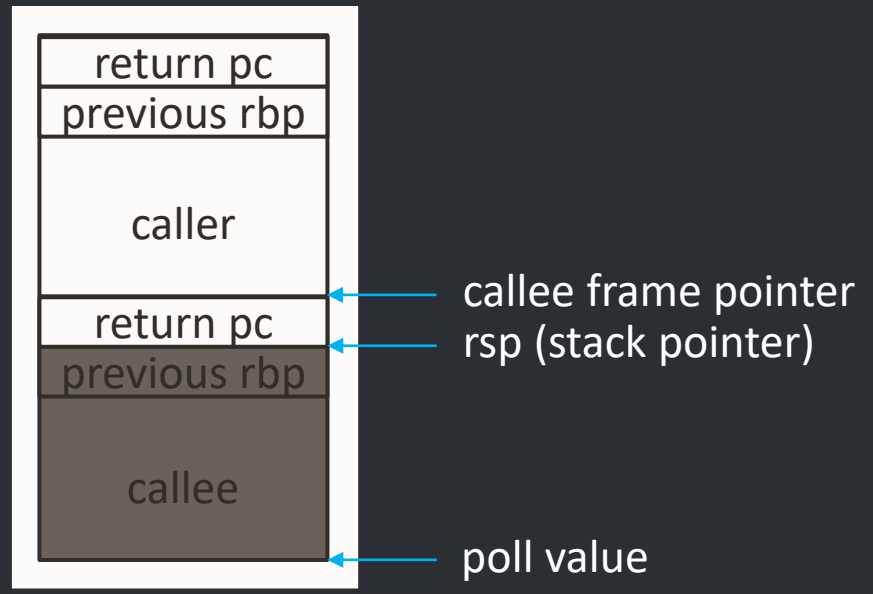


Compiled Method Epilog

x86_64 assembly

~~movq rtmp, 0x330(r15)~~
~~testb rax, 0x0(rtmp)~~

cmpq rsp, 0x338(r15)
ja slow_path



Interpreter Method Epilog

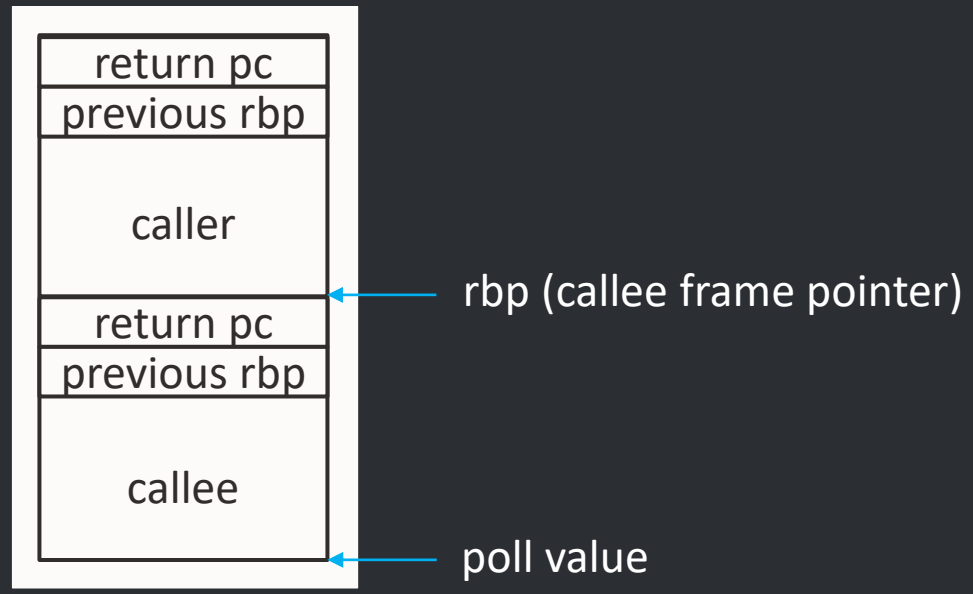
Overview

- Frame pointer is available
- Poll happens ***before*** unwinding
  - This is why initial processing needs 3 frames
  - A new GC phase shift can happen in the unwind handler, before top frame is unwinded
  - Expectation after unwinding is at least top 2 frames are processed

Interpreter Method Epilog

x86_64 assembly

```
cmpq rbp, 0x338(r15)
ja  slow_path
```



Loop safepoint polls

Overview

- Compiled methods: same as before (indirect load)
- Interpreter: check if low order bit is set

Loop polls

x86_64 assembly

Interpreter:

```
testq 0x338(r15), 0x1
jnz  slow_path
```

Compiled:

```
movq rtmp, 0x330(r15)
testb rax, 0x0(rtmp)
```

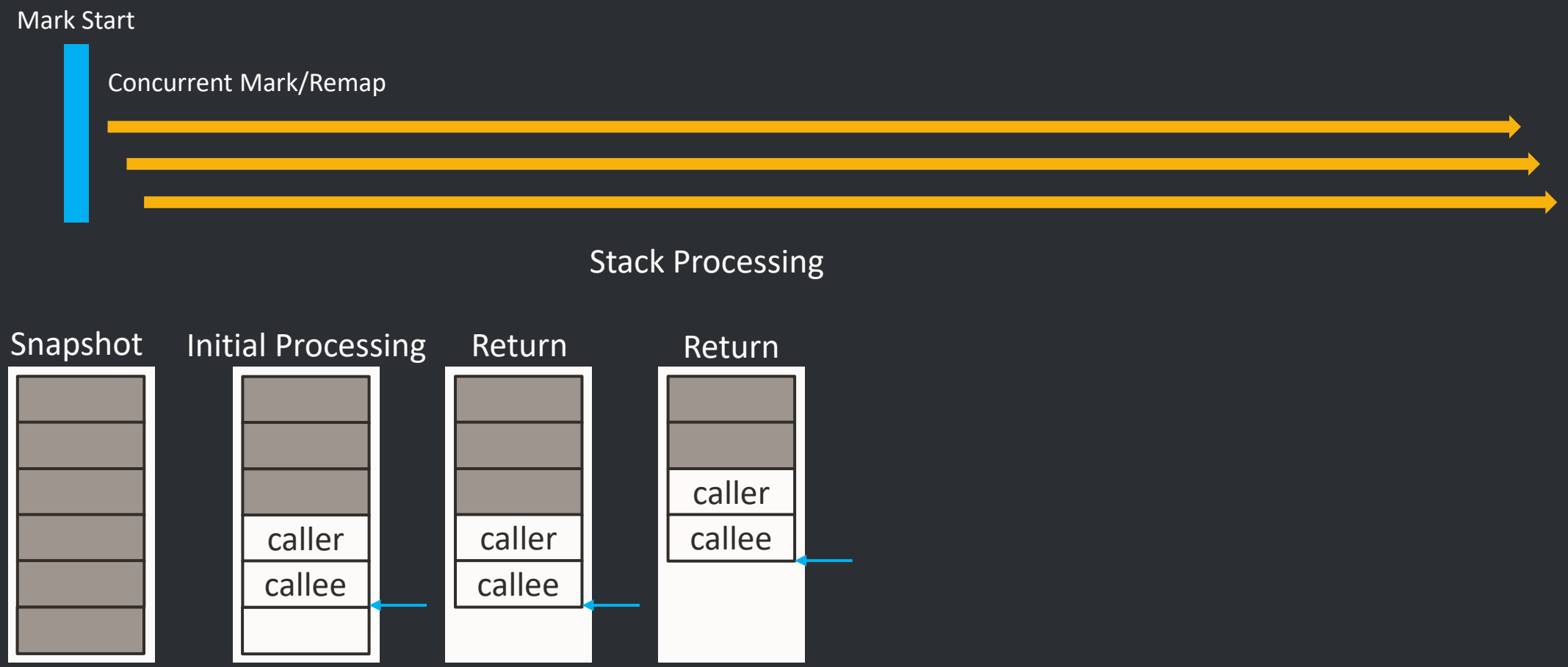
Stack Watermark Barrier

Intercepting dangerous returns

Thread-local poll value	Stack Watermark	Safepoint	Thread-local handshake
0xFFFFFFFFFFFFFFFE	None	None	None
0x1	None	Pending	None
0x1	None	None	Pending
0x1	None	Pending	Pending
0x1	Invariant breaks when unwinding some frame	Pending	None
0x1	Invariant breaks when unwinding some frame	None	Pending
0x1	Invariant breaks when unwinding some frame	Pending	Pending
$callee_sp	Invariant breaks when unwinding frame for $callee_sp	None	None

Stack Processing Overview

What we want to do



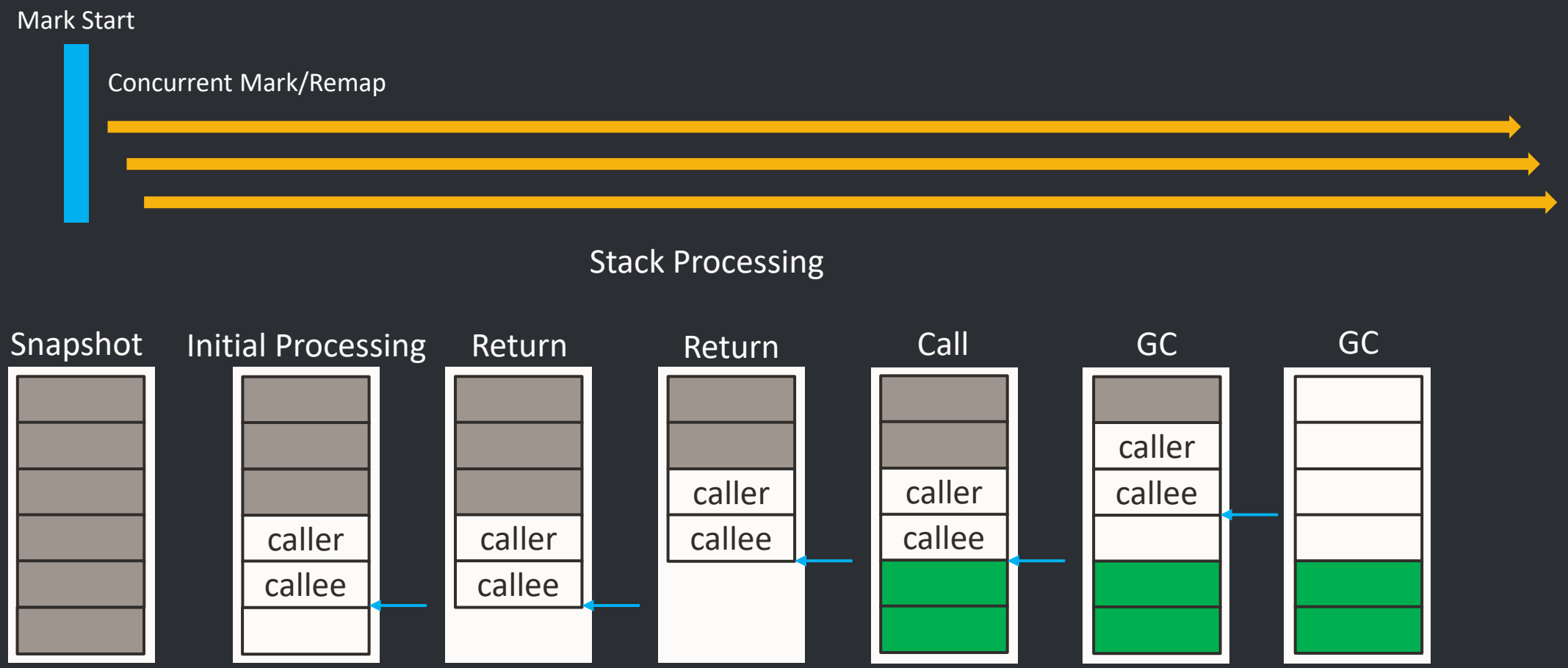
Stack Watermark Barrier

Intra-thread interactions

- GC thread wants to process frame of Java thread
- Take lock
- Process caller of “caller”
- Update caller/callee relationship one frame up in the stack
- Release lock
- Thread-local poll value may only be updated by the thread itself
  - Need to perform an acquire to make concurrent stack changes visible

Stack Processing Overview

What we want to do



Stack Watermark Barrier

Intra-thread interactions cont.

- Non-GC threads may also access thread internals of a remote thread
- Initial processing done under the lock
  - Can be triggered by other threads
- Used by thread-local handshakes to make remote thread access safe

Stack Watermark Barrier

Stack walkers

- JVM has stack walkers, reading object references deeper into the stack
- Can’t read object references from stack with load barriers
  - Object-internal pointers break
- JVM-internal stack walking API hooks to process frames in the stack watermark
  - When asking for frame caller, ensure it is processed before exposing it
- Must initialize processing first
- Any thread may initialize processing on any other thread
- Must grab hold of thread to walk its stack
  - Current thread: always initialized
  - Thread-local handshake: forces initialization
  - Safepoint: forces initialization (for random GC-unaware safepoints)
  - Async call trace: inaccurate; can’t read object references
  - JFR stack sampling: inaccurate; can’t read object references
  - …

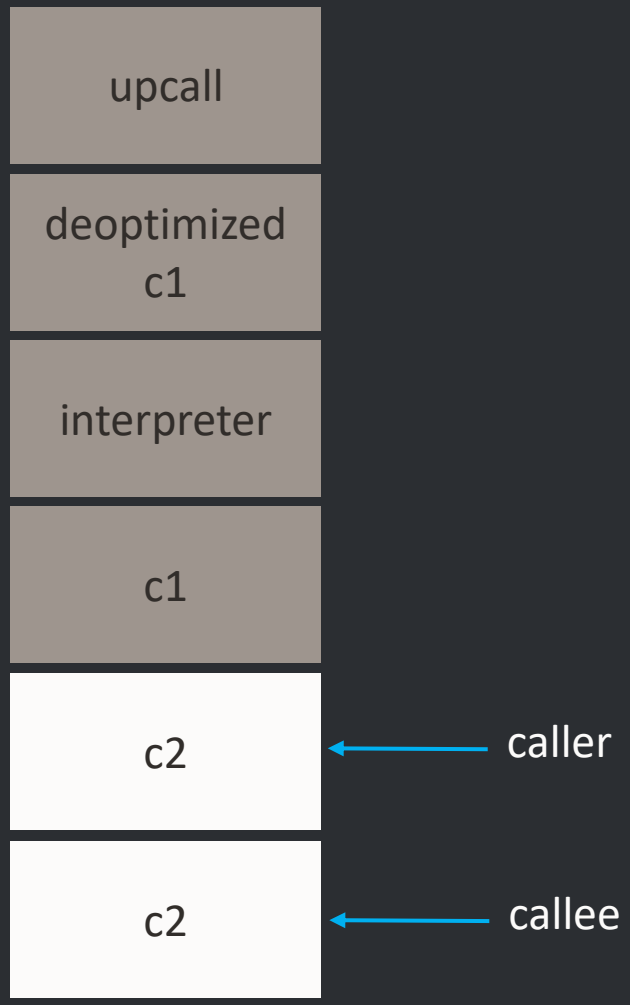
Stack Watermark Barrier

Exception handling

- So we figured out returns, but what about **throw**?
- Every type of frame has an exception handler, invoked when its callee unwinds into the caller
- Exception handler invoked **after** unwinding

Stack Watermark Barrier

Exception handling



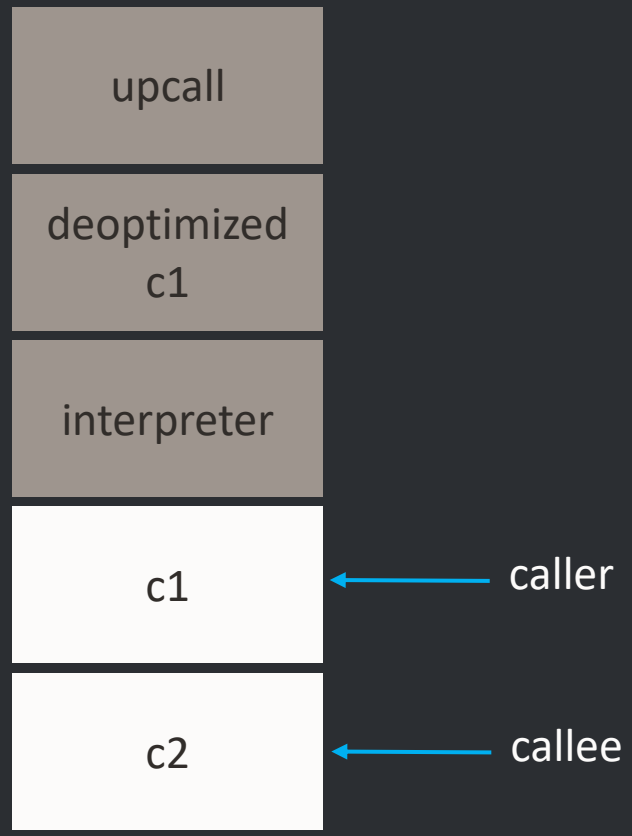
Stack Watermark Barrier

Exception handling

Stack Watermark Barrier

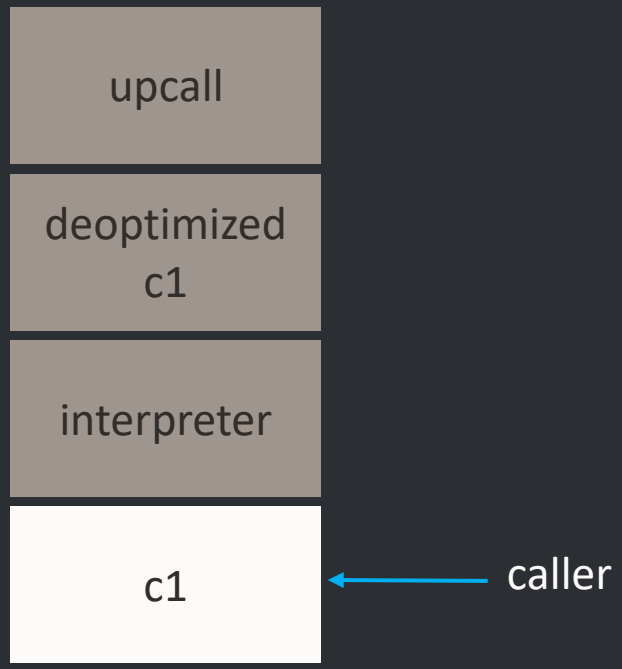
Exception handling

Process frame in c2 exception handler **after** unwinding



Stack Watermark Barrier

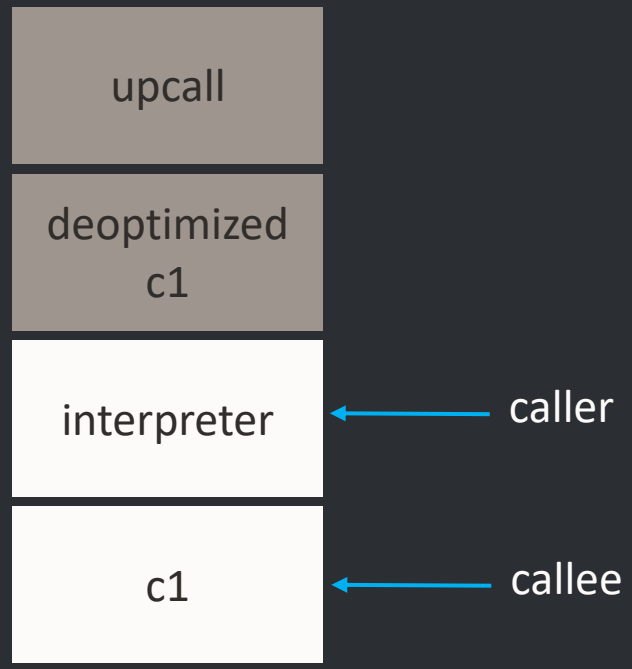
Exception handling



Stack Watermark Barrier

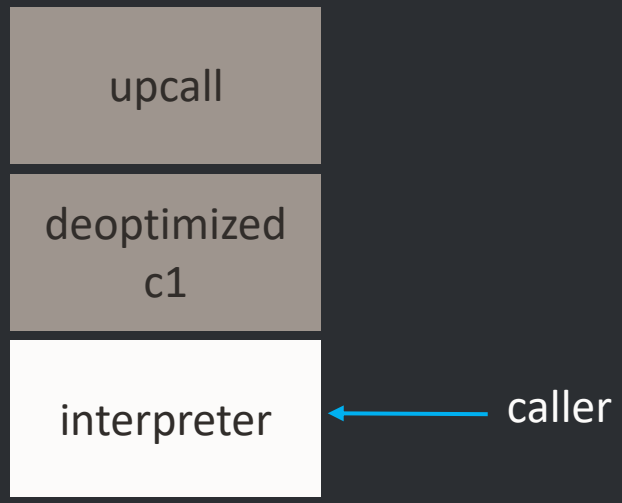
Exception handling

Process frame in c1 exception handler **after** unwinding



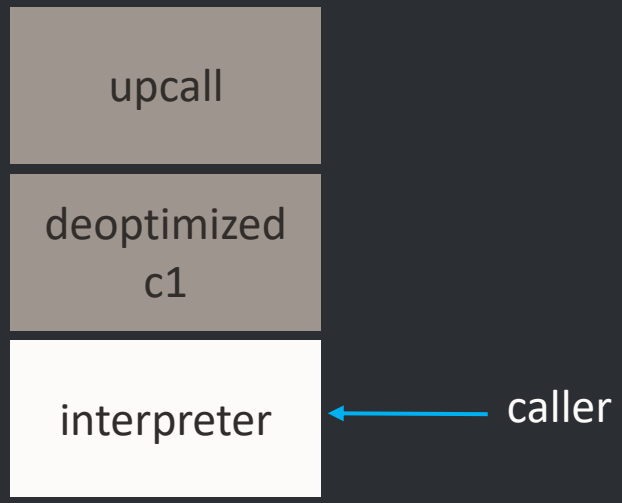
Stack Watermark Barrier

Exception handling



Stack Watermark Barrier

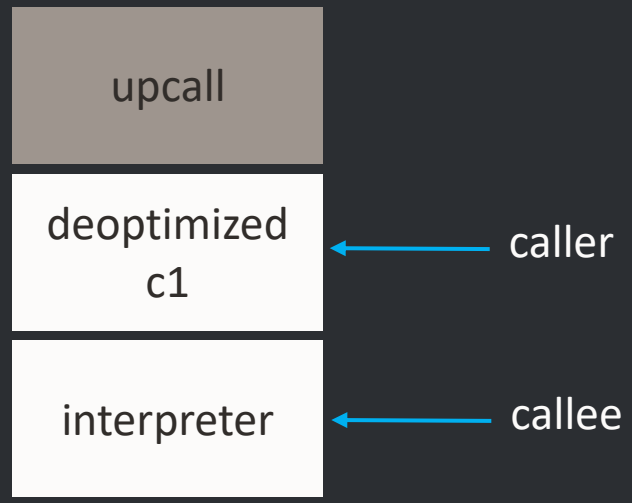
Exception handling



Stack Watermark Barrier

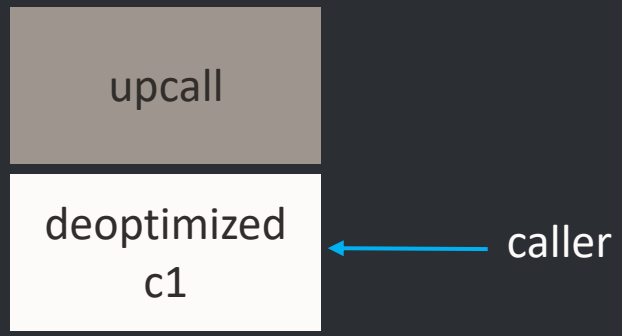
Exception handling

Process frame in interpreter exception handler **after** unwinding



Stack Watermark Barrier

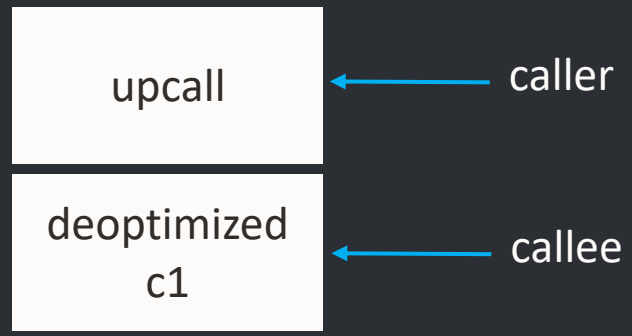
Exception handling



Stack Watermark Barrier

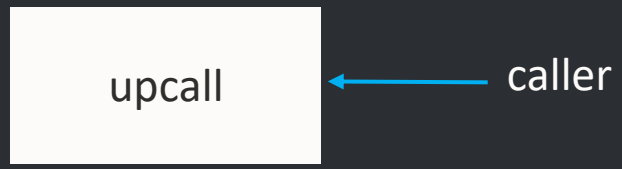
Exception handling

Process frame in depot with exception handler **after** unwinding



Stack Watermark Barrier

Exception handling



Process frame in upcall exception handler **after** unwinding

Stack Watermark Barrier

Exotic unwinding

- On-stack-replacement
  - Unwind interpreter frame, replace with compiled frame
- Deoptimization
  - Unwind compiled frame, replace with interpreted frame
- JVMTI pop frame
- JVMTI force early return
- Unwinding from native code

Stack Watermark Barrier

How to process a frame

- Need to find object references, and fix them
  - During relocation phase
    - Relocate objects that need to move
    - Remap references to objects that have been relocated
    - Fix pointer colors (to “remapped” color)
  - During marking phase
    - Lazily remap object references
    - Mark objects as live
    - Fix pointer colors (to some “marked” color)

Stack Watermark Barrier

How to process a frame

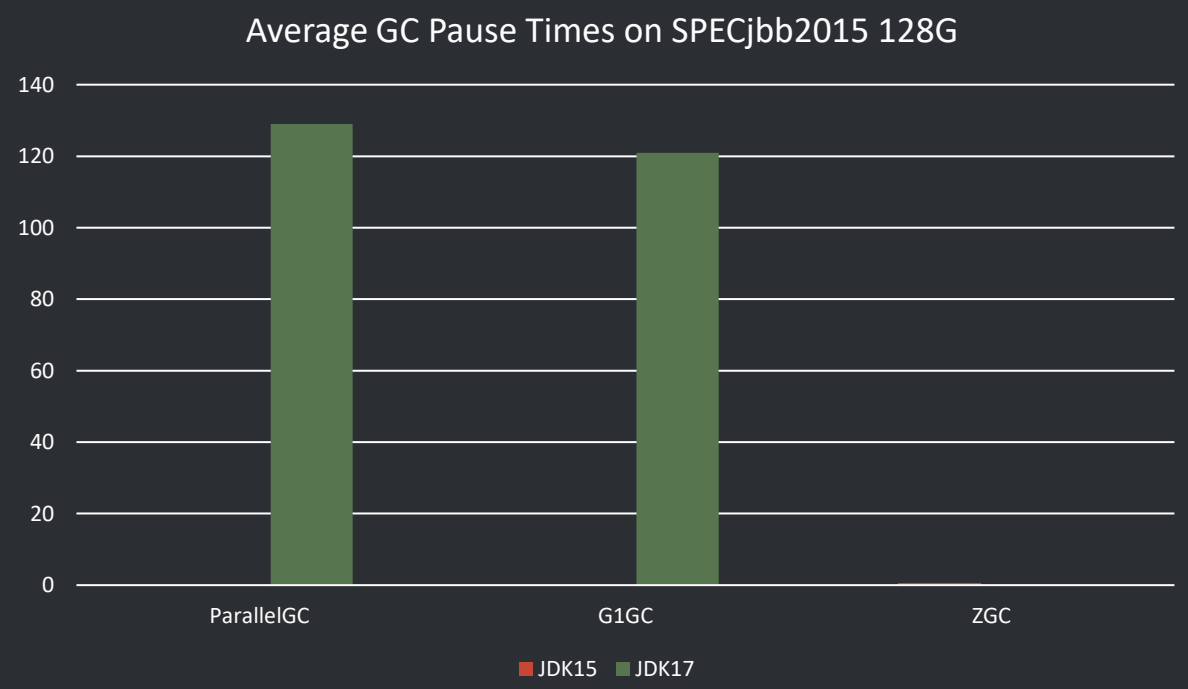
- Object references can be found embedded in the frame
- Can also be found embedded in compiled method of frame
  - Lazily apply compiled method entry barriers
    - Usually invoked on first call to a method, per GC phase
    - Update embedded object references
    - Disarm compiled method entry barrier

Stack Watermark Barrier

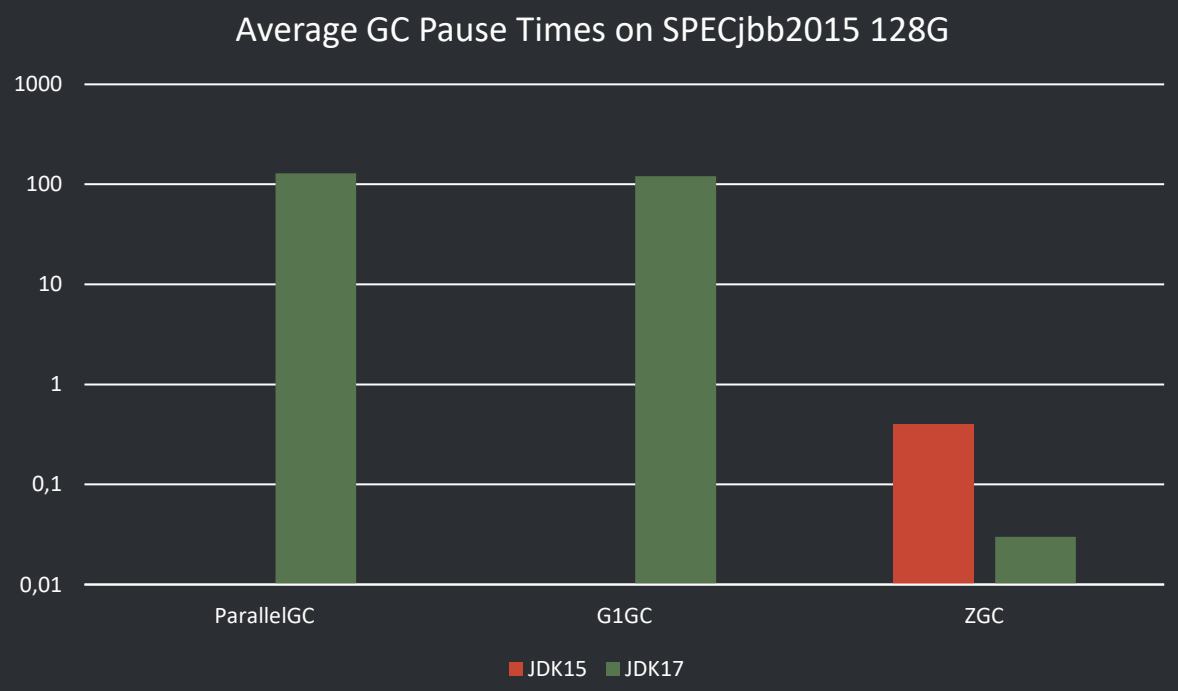
Extensibility

- All this logic is hidden in a shared HotSpot framework
- Specific user of the API only needs to specify
  - how to process a frame
  - how to detect GC phase change if applicable
- Shenandoah adopted this
- Discussions about using it for optimized JFR stack sampling

Evaluation
GC pause times



Evaluation
GC pause times



Questions

The End