Performance Through Parallelism: Java HotSpot™ GC Improvements

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TS-1168

Our Goal—Convert This:

Q: Why does GC take so long?
<grumble, grumble...>

A: It starts at the roots and...

Into This:

Q: How does GC go so fast?

A: It uses parallelism and concurrency and...

Agenda

Motivation

Terms and Taxonomy

Parallel Scavenge

Concurrent Mark Sweep

Parallel Compaction

What's Cooking in the Lab

Summary

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Why Parallel?

Hardware Trends

- Multiple…
  - Chips per box
  - Cores per chip
  - Threads per core
- Sun, AMD, IBM, Intel
  - Shipping or developing multi-threaded, multi-core products
- 64-bit addressing
  - Allows huge heaps

Why Parallel?

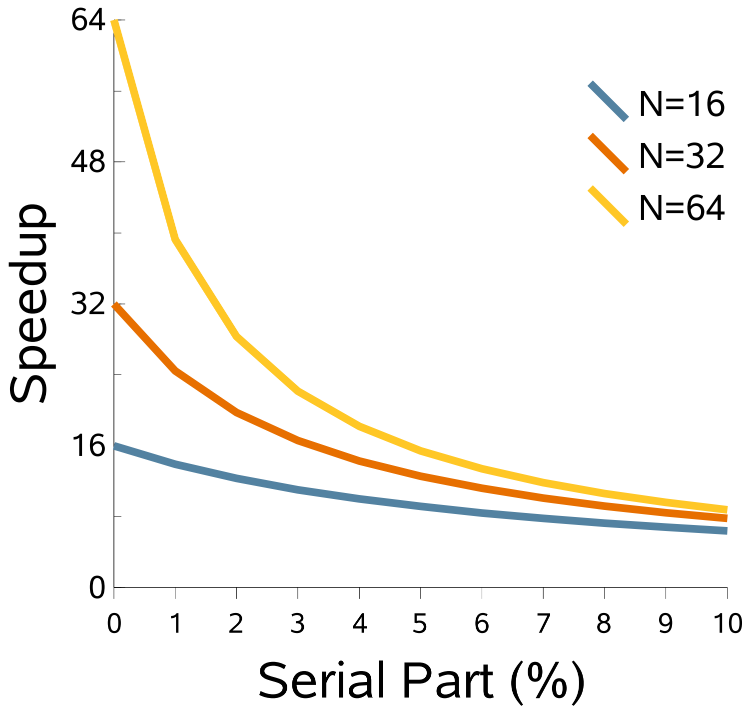
Java Programming Language

- Built-in support
- Threads allow parallelism
- java.util.concurrent APIs enable parallelism
  - Lock-free data structures
  - Locking primitives
  - Available in Java platform 5 and later

Why Parallel?

Amdahl's Law

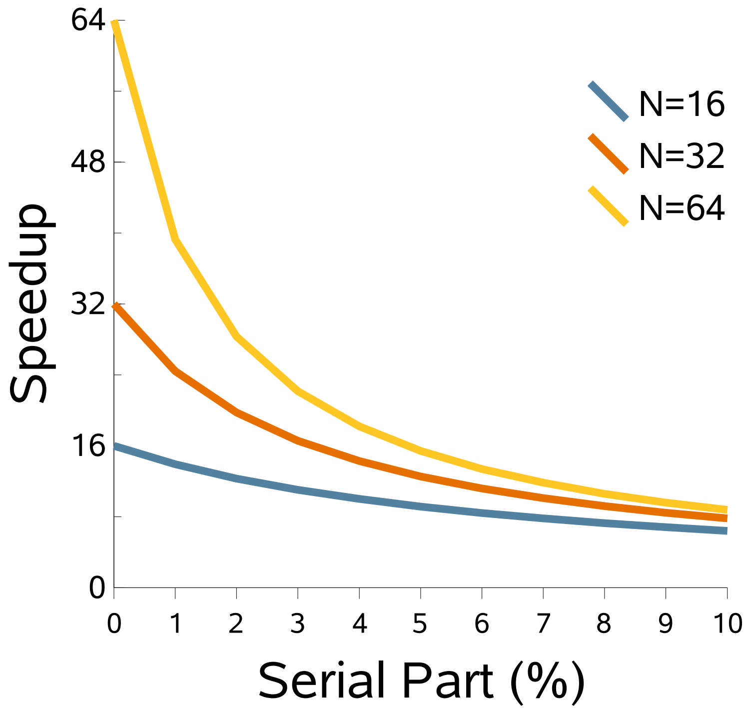
- Speedup =
  1/(Serial Part + (Parallel Part / N))



Why Parallel?

Amdahl's Law

- Many threads create garbage
- Just one thread to clean it up?
  - GC would become a serial bottleneck



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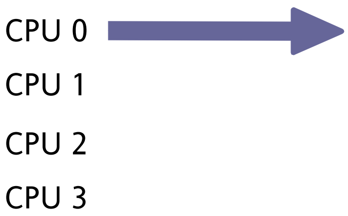
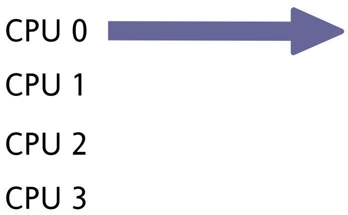
Terms

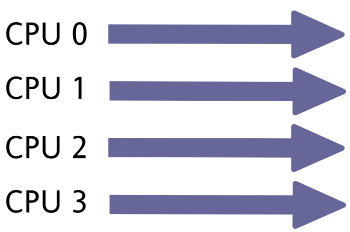
- Serial
  - One thing happens at a time



Terms

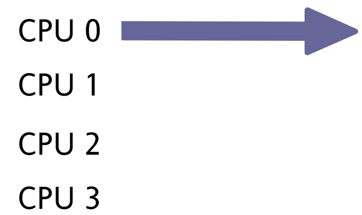
- Serial
  - One thing happens at a time
- Parallel
  - Multiple things happen at once
  - Single task
    - Split into parts
    - Executed simultaneously





Terms

- Serial
  - One thing happens at a time



- Parallel
  - Multiple things happen at once
  - Single task
    - Split into parts
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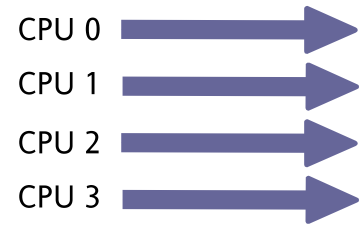
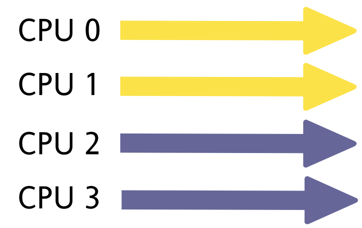


- Concurrent
  - Multiple things happen at once
  - Multiple tasks
    - Different purposes
    - Execute simultaneously
    - Here: Java technology tasks vs. GC tasks

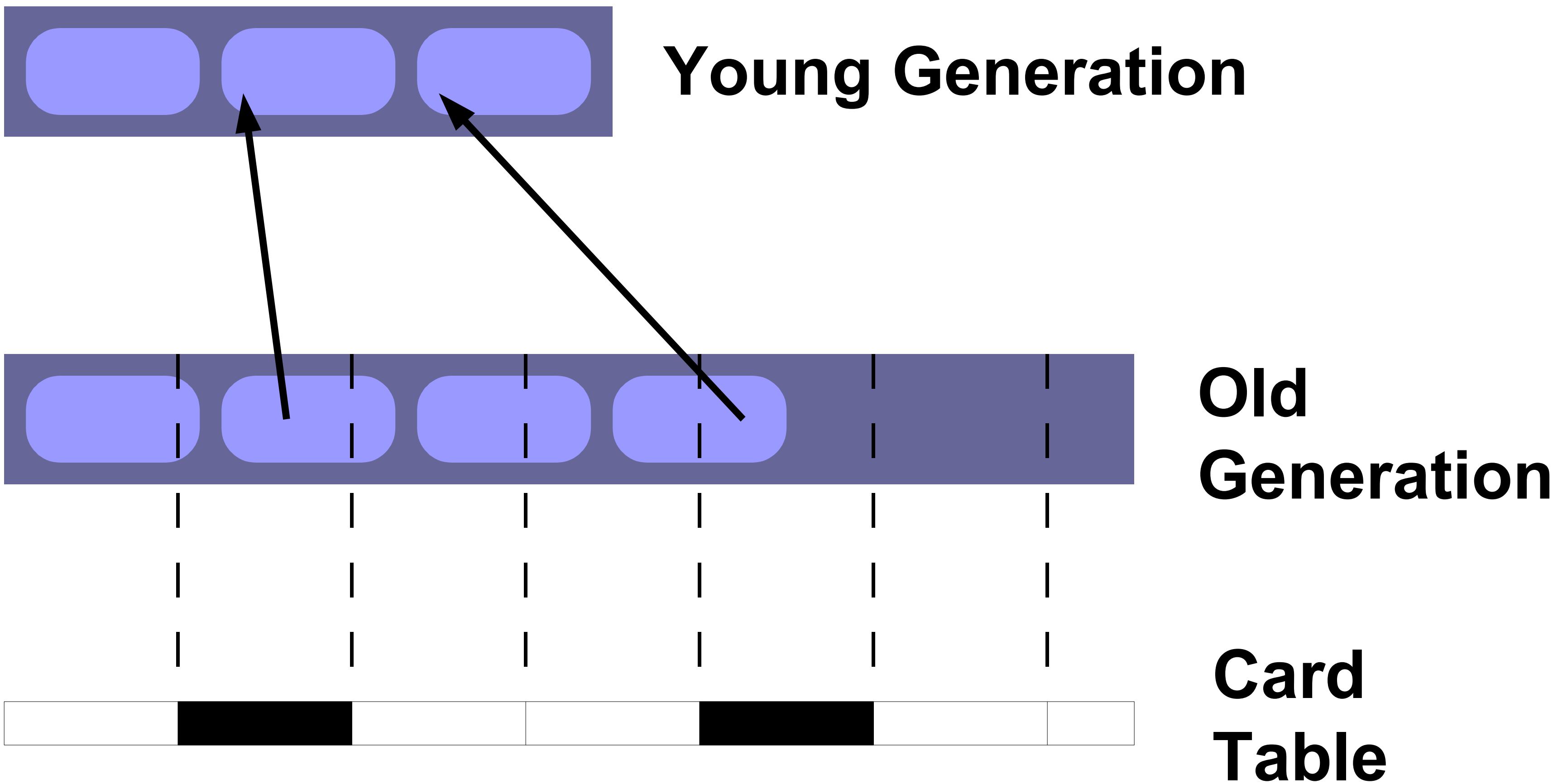


Taxonomy

- Generational GC
  - Observation: most objects die young
  - Segregate objects
    - New objects—allocated in the ‘young generation’
    - Old objects—promoted to the ‘old generation’
  - Collect young generation more frequently
    - Use algorithm optimized for ‘mostly dead space’
  - Pros:
    - Efficient—work a little, reclaim a lot
    - Most pauses are shorter—scan only part of the heap
  - Cons:
    - Some extra bookkeeping
    - Eventually must collect entire heap

Generations in HotSpot

Old-to-Young References



Taxonomy

- Stop-the-World GC
- Typical cycle:
  - Stop all Java technology threads
  - Do GC work
  - Restart all Java technology threads
- Pros:
  - Simpler—heap is frozen, objects not changing
- Cons:
  - Some applications sensitive to pause times

Taxonomy

- Concurrent GC
- Typical cycle:
  - Start GC
  - Java technology threads continue to run
    - During most or all of GC cycle
  - Finish GC
- Pros:
  - Pause times are short (or non-existent)
- Cons:
  - Must take extra care—objects are changing
  - Some overhead—performance, heap size

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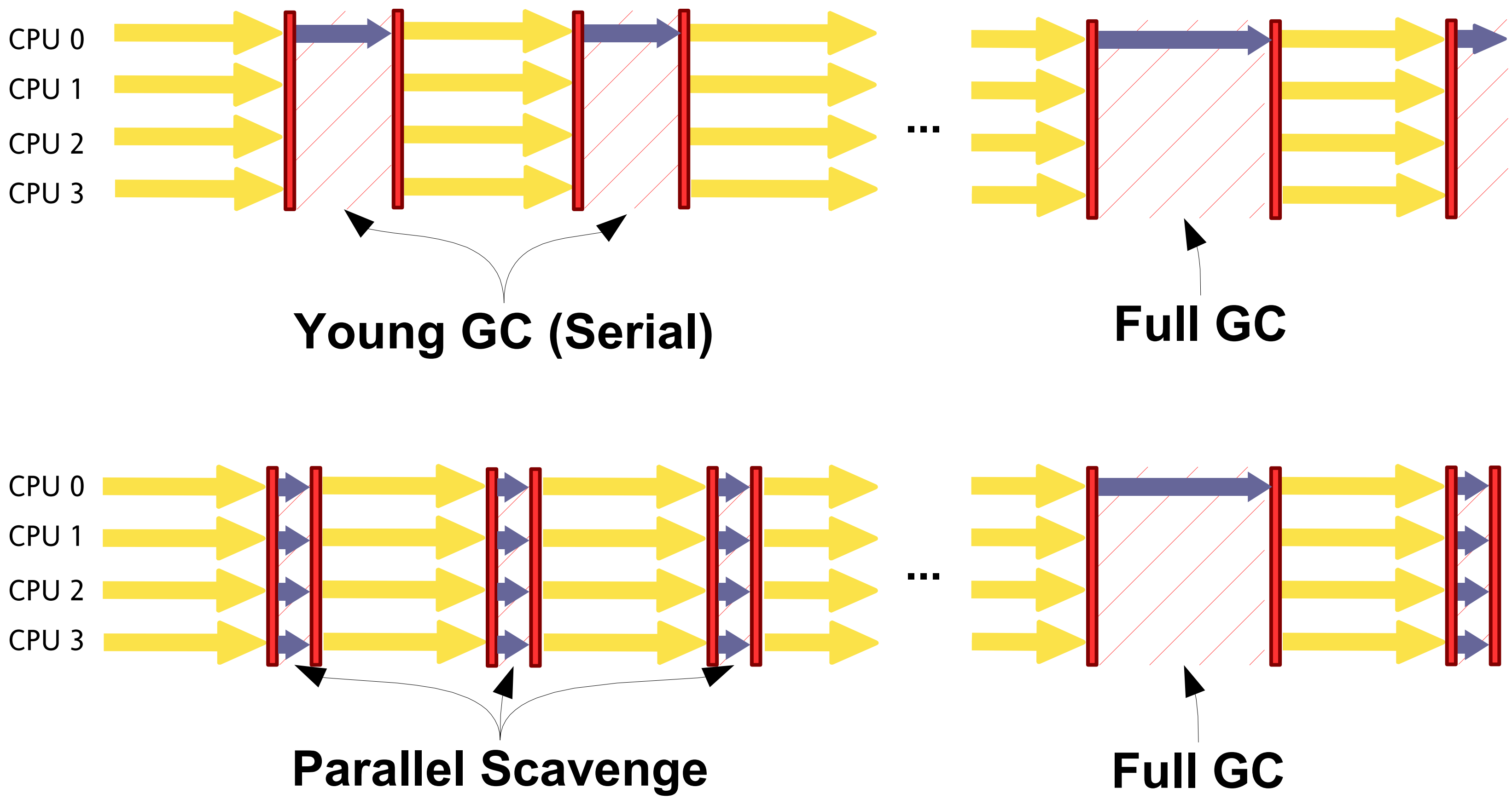
Parallel Scavenge

- Generational, stop-the-world, parallel
- Collects young generation only
- Available since JDK™ 1.4.2 software
  - Experimental in JDK 1.4.1 software
- First parallel GC in Java HotSpot performance engine
  - For many applications
  - Majority of GC time is spent on young generation
- -XX:+UseParallelGC

Typical GC Pattern

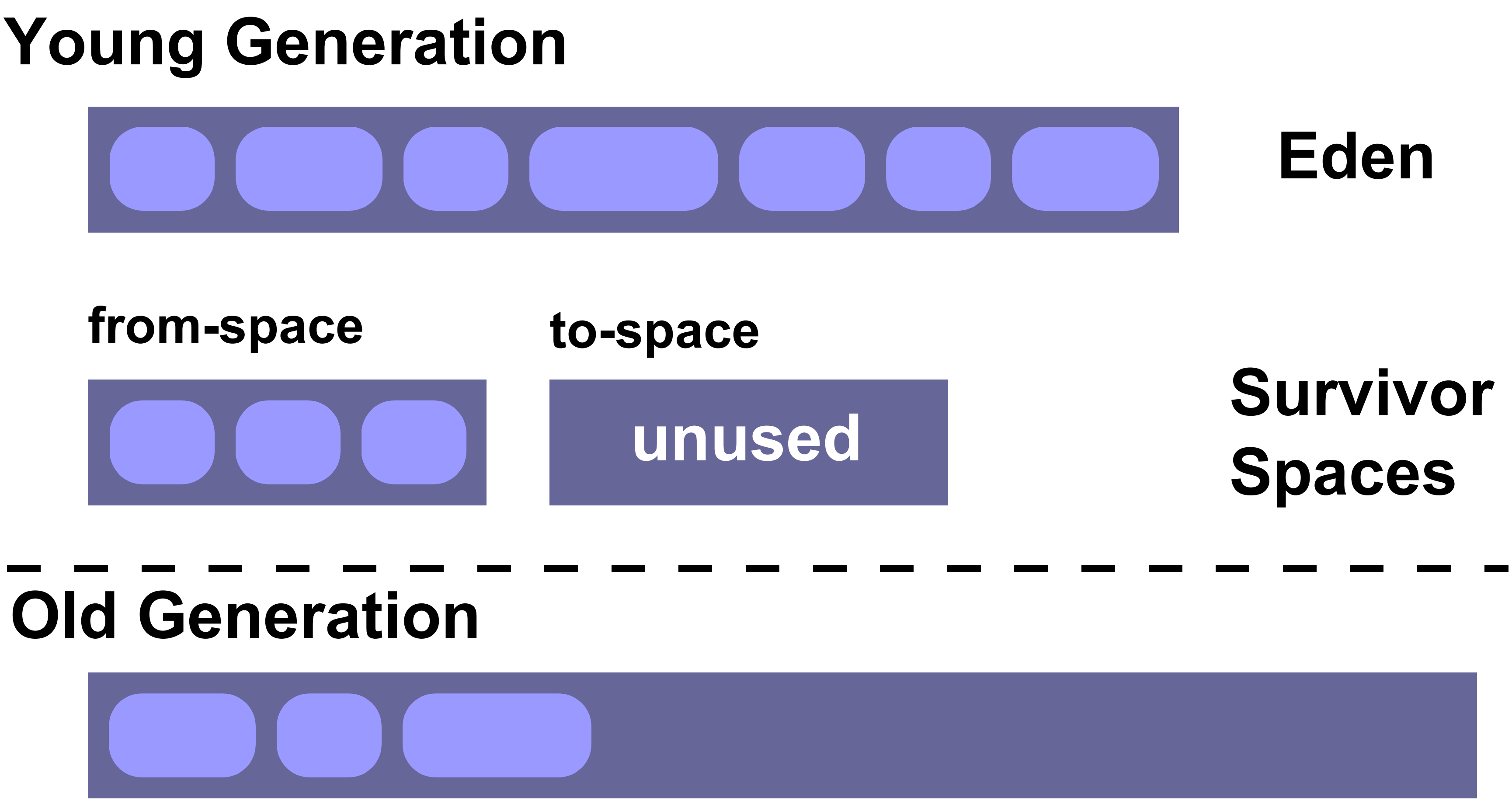


Parallel Scavenge

Basic Algorithm

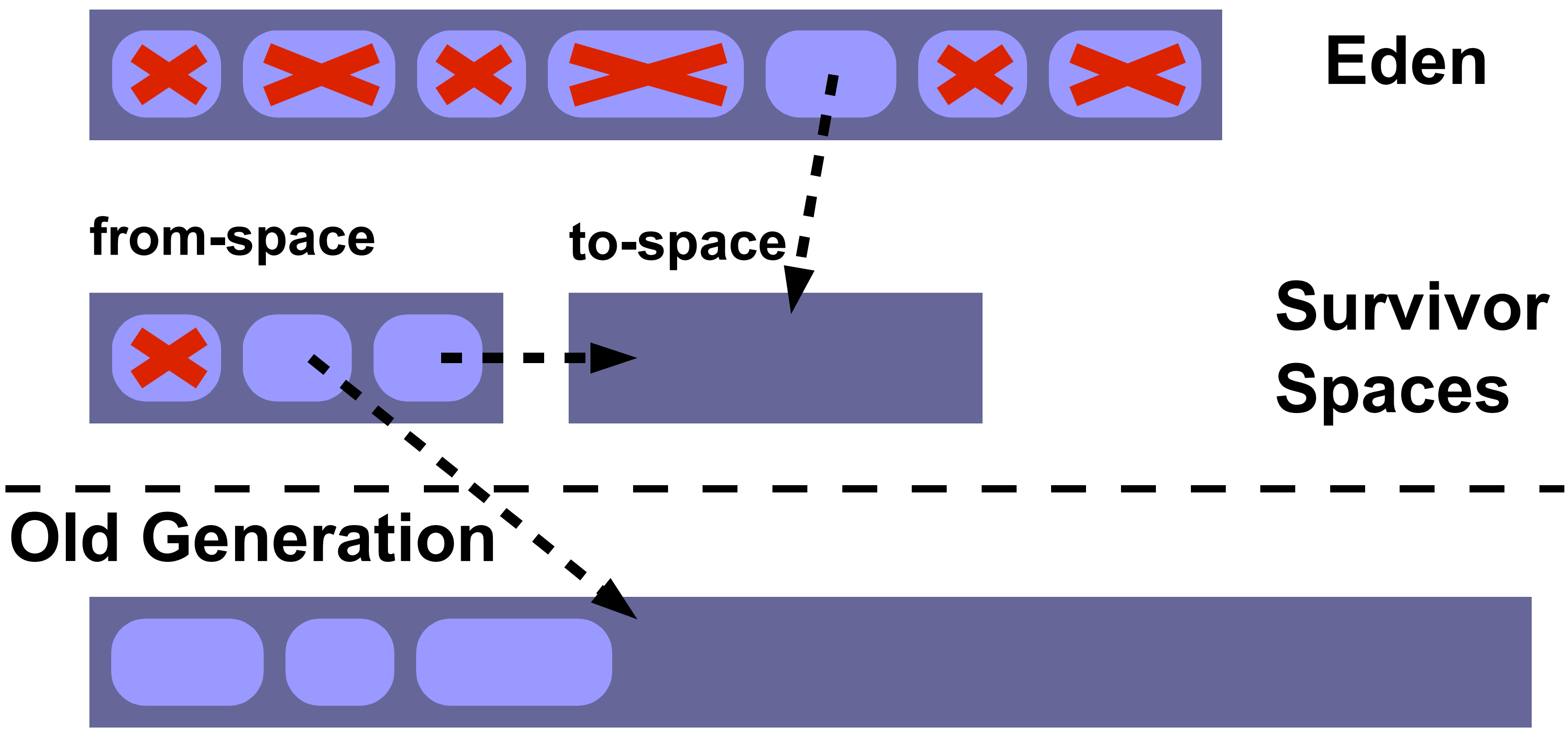
- Divide root set among GC threads
- Trace reachable objects in young generation
  - Atomic instruction (CAS) used to claim an object
- As objects are claimed, they are copied
  - Young-ish objects copied to to-space
  - Old-ish objects promoted into old generation
  - Use per-thread buffers in destination spaces
    - Fast, lock-free allocation
- At end, eden and from-space are empty
  - from-space and to-space switch roles

Scavenge Example—Before

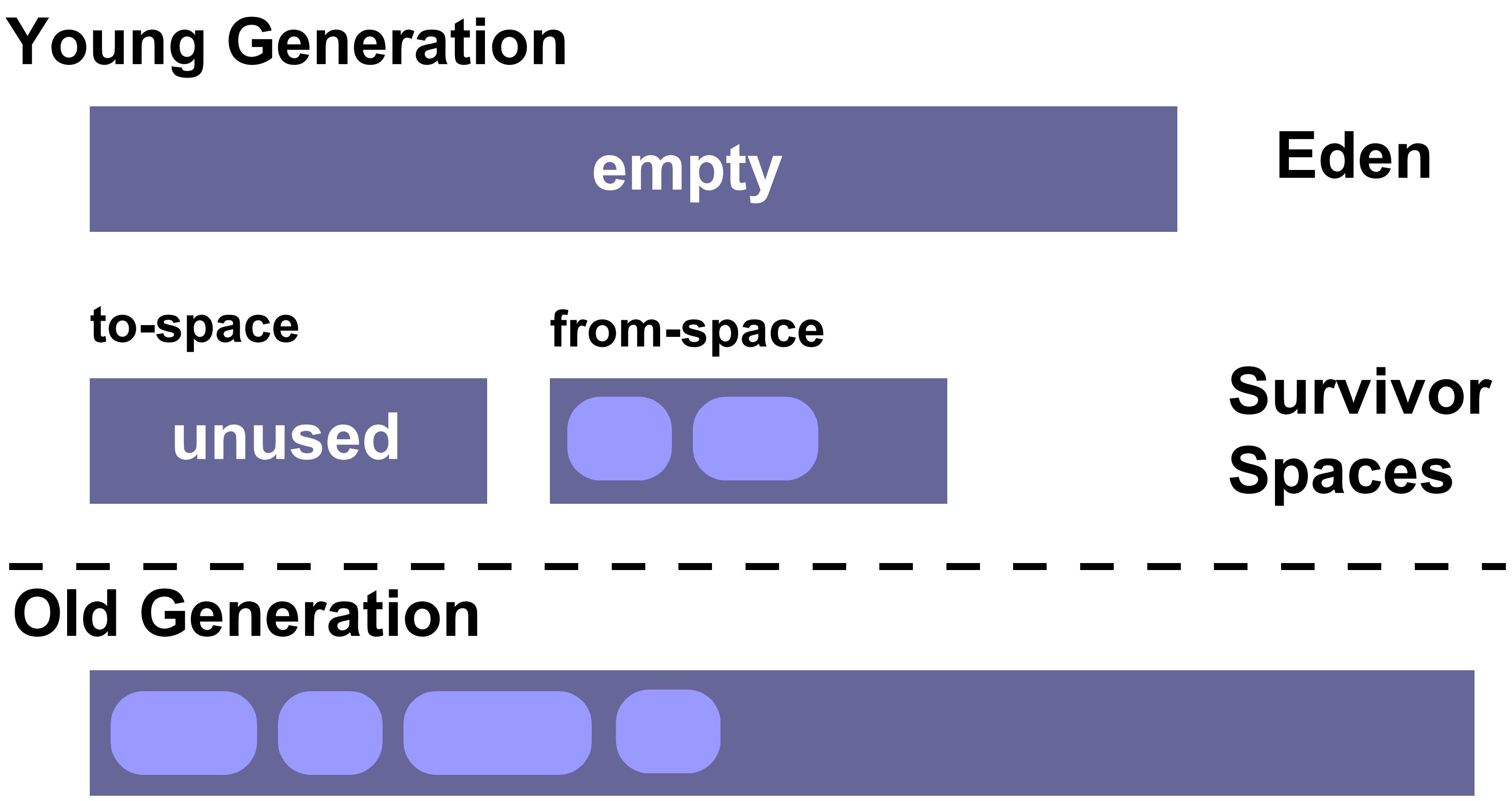


Scavenge Example—During

Young Generation



Scavenge Example—After



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- Parallel Compaction
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Concurrent Mark Sweep

- Generational, mostly concurrent, parallel, non-moving
  - Collects old and permanent generations only
  - Paired with Parallel Scavenge
    - (Serial scavenge on uniprocessor)
  - Most work done concurrently with Java technology threads
  - Available since JDK 1.4.2 software
    - Experimental in JDK 1.4.1 software
  - -XX:+UseConcMarkSweepGC

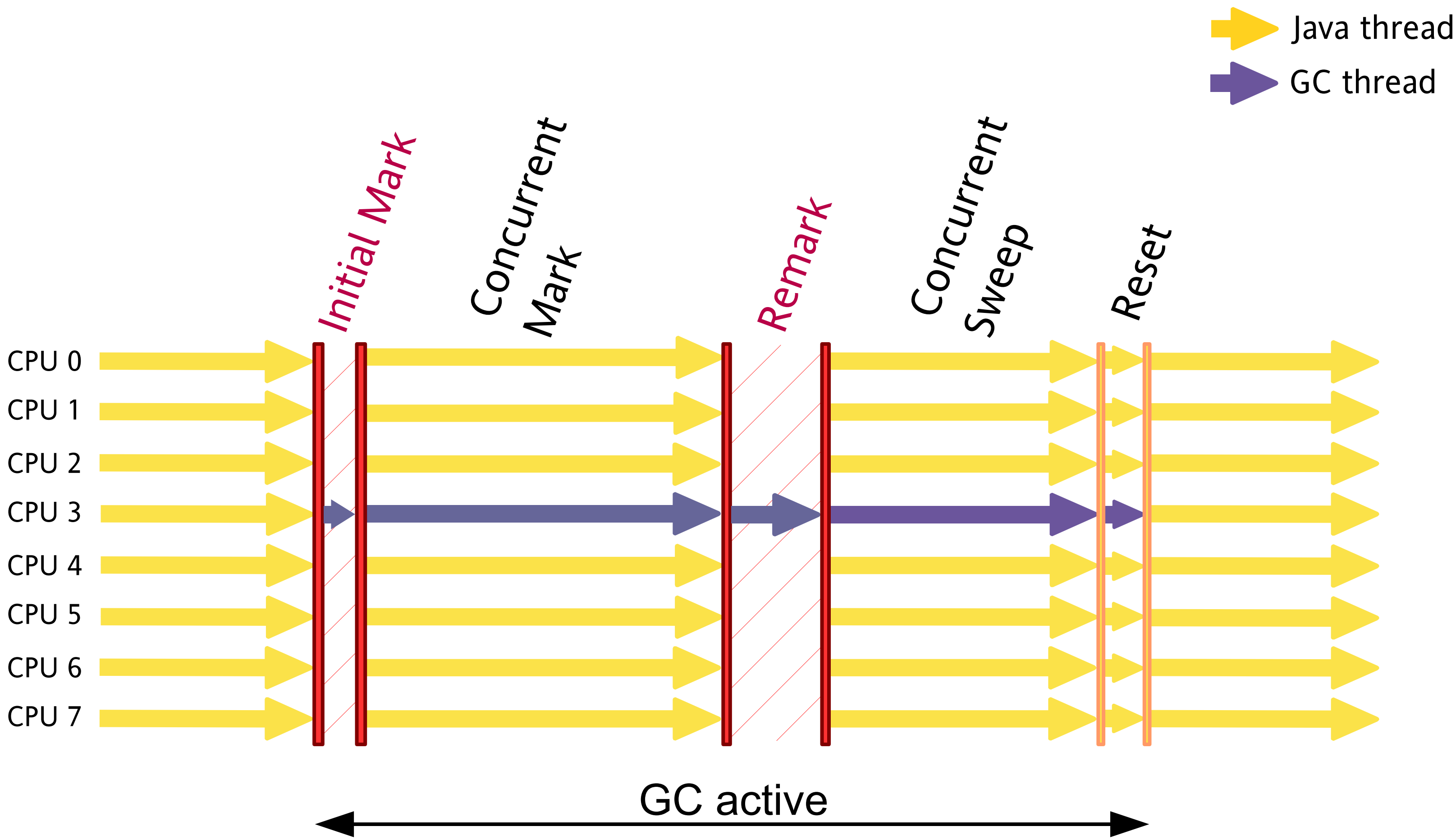
Concurrent Mark Sweep

- Non-moving
  - Once promoted into old generation, object does not move(*)
  - Free lists used for allocation
    - Somewhat slower than ‘pointer-bumping’
- Dealing with fragmentation
  - Track popular object sizes
  - Estimate future demand
  - Split or join free blocks to meet demand
- Serial Mark Sweep Compact used as fallback
  - (*) Will move old generation objects

Concurrent Mark Sweep

- Concurrent Mark Sweep Phases
  - Initial mark
    - Stop-the-world pause to mark from roots
    - Not a complete marking—only one level deep
  - Concurrent mark
    - Mark from the set of objects found during Initial Mark
  - Remark
    - Stop-the-world pause to complete marking cycle
    - Ensures a consistent view of the world
  - Concurrent Sweep
    - Reclaim dead space, adding it back onto free lists
  - Concurrent Reset

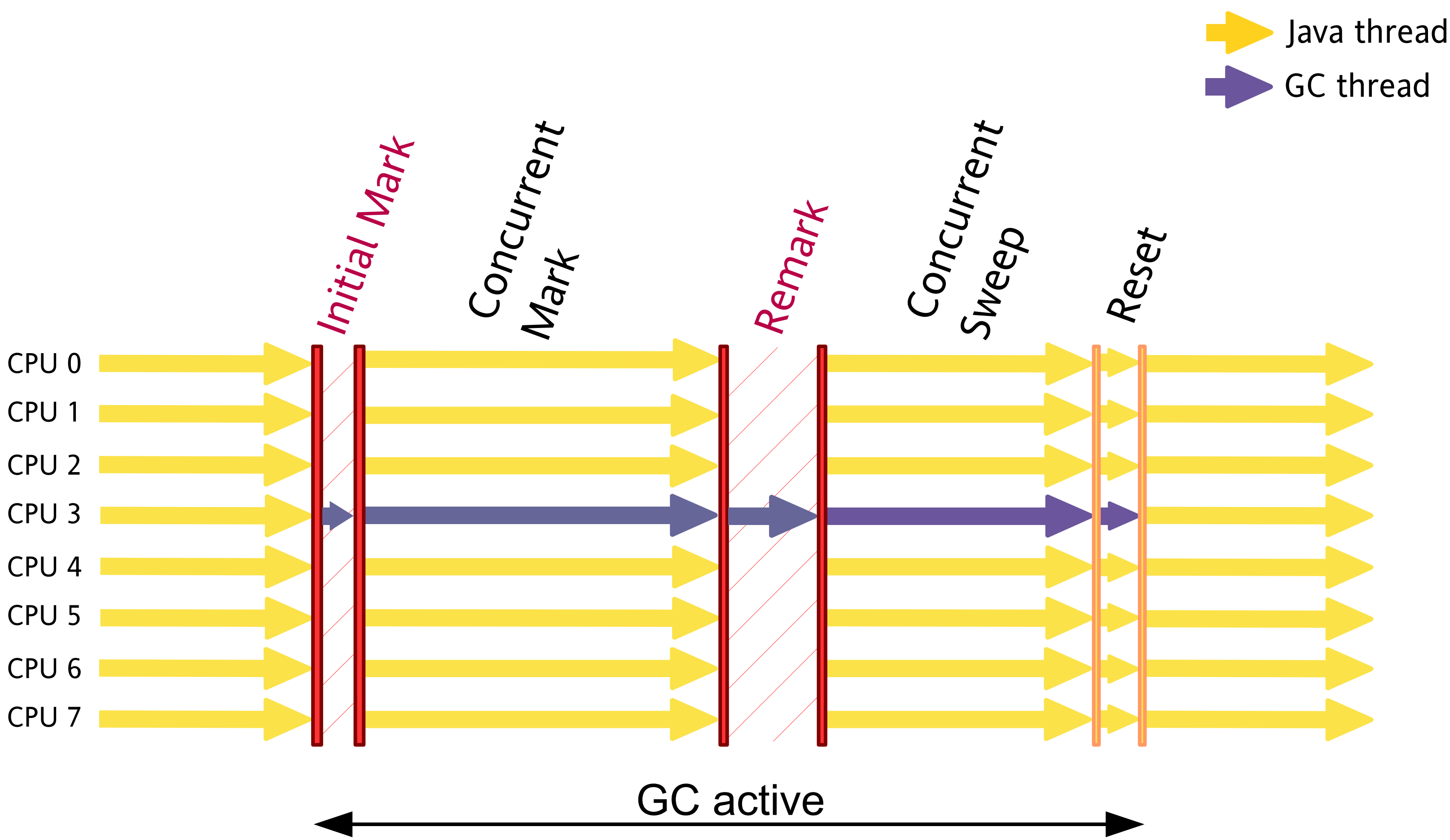
Concurrent Mark Sweep Phases



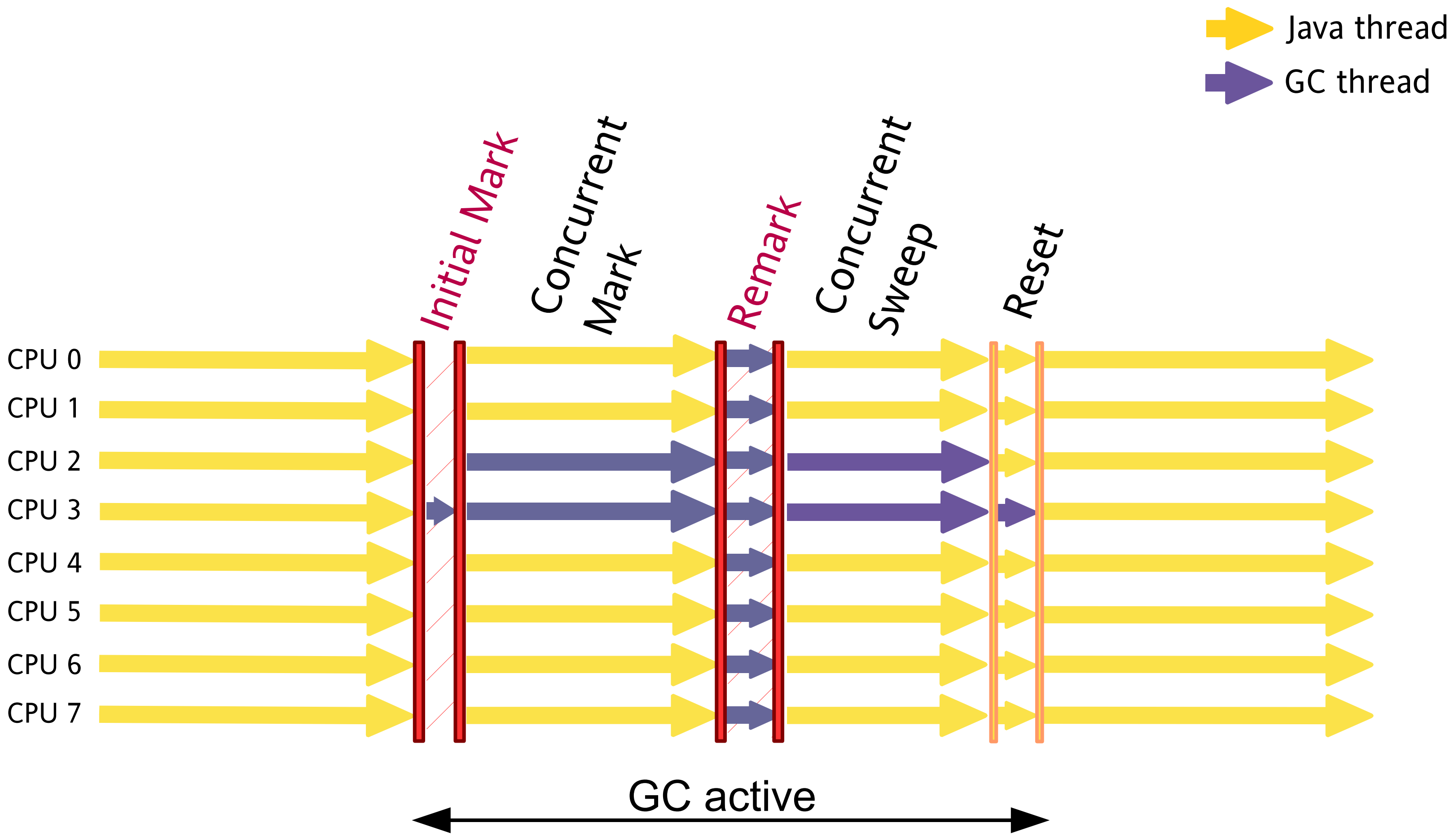
Concurrent Mark Sweep

- The need for Parallelism
  - Remark is typically the largest pause
    - Often larger than Young GC pauses
    - Parallel remark available since Java 5 platform
  - Single marking thread
    - Can keep up with ~4–8 cpus, usually not more
    - Parallel concurrent mark available in Java 6 platform
  - Single sweeping thread
    - Less of a bottleneck than marking
    - Parallel concurrent sweep coming soon

Concurrent Mark Sweep Phases



Concurrent Mark Sweep Phases



DEMO

Concurrent Mark Sweep

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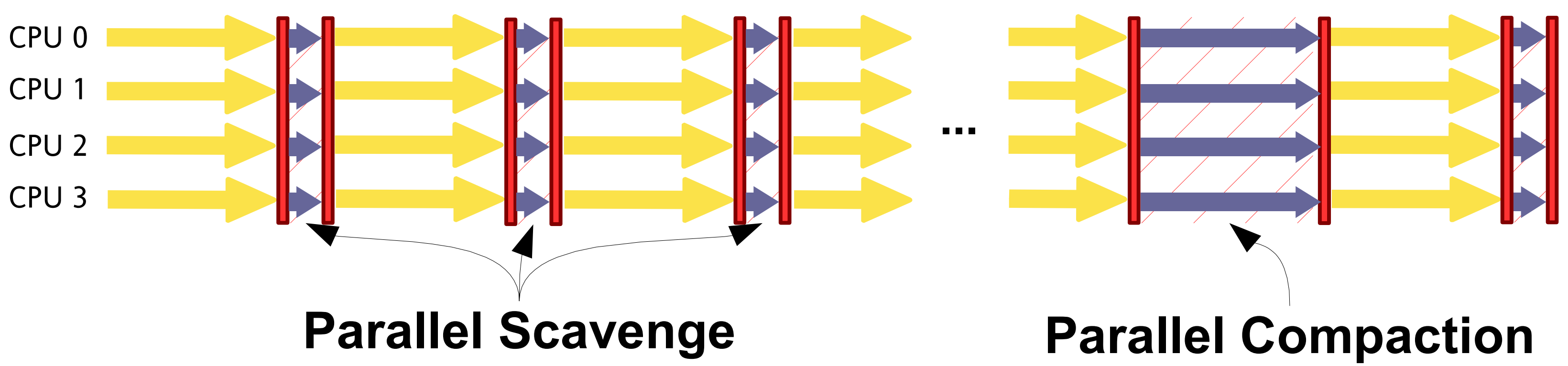
Parallel Compaction

- Stop-the-world, parallel, sliding compaction
  - New! Available in Java EE 5 update 6
  - Full GC—collects entire heap
  - Paired with Parallel Scavenge
  - -XX:+UseParallelOldGC



Parallel Compaction

- Three phases: marking, summary, compaction
- Heap divided into fixed-sized regions
  - Marking records information about each region
  - Used later to enable compaction in parallel
- Sliding compaction—preserves object order
  - Possible cache benefits

Marking Phase

- Divide root set among GC threads
- Trace all live objects, in parallel
  - Objects claimed atomically
  - Liveness recorded in an external bitmap
- Once object is claimed, update per-region data
  - Add object size to region total
  - Extra bookkeeping if object extends onto other regions

Summary Phase

- Compute the "dense prefix"
  - Block of very dense regions on the left
    - Nearly all objects are live
    - Remainder are not reclaimed (dead wood)
  - Per-region liveness data guides selection
  - Find the prefix with the best reclamation ratio
    - Space reclaimed/data copied
- Compute destination of each region
  - Where the first live byte in the region will go

Summary Phase (Cont.)

- Additional data saved for each region
  - Source region
  - Destination count
- Summary phase currently done serially
  - Can be parallelized
  - Not as important for performance
    - Operates on regions, not objects

Compaction Phase

- Fill regions, in parallel
- First identify available regions
  - Empty regions
  - Regions that compact only into themselves
- Then threads claim available regions atomically
  - Once claimed, no other synchronization required
  - Fill the region, repeat

Compaction Phase (Cont.)

- Filling a region
  - Find the first byte destined for this region
  - Copy objects until region is full (or nothing left to copy)
  - Do some bookkeeping for source regions
- Easy!

Compaction Phase (Cont.)

- Filling a region
  - Find the first byte destined for this region
    - Start with source region
    - May have to skip over some objects
      - Consult bitmap for liveness info
  - Copy objects until region is full (or nothing left to copy)
  - Do some bookkeeping for source regions

Compaction Phase (Cont.)

- Filling a region
  - Find the first byte destined for this region
  - Copy objects until region is full (or nothing left to copy)
    - Must find live objects and skip dead space
      - Consult bitmap
  - Do some bookkeeping for source regions

Compaction Phase (Cont.)

- Filling a region
  - Find the first byte destined for this region
  - Copy objects until region is full (or nothing left to copy)
    - Must find live objects and skip dead space
      - Consult bitmap
    - Must update interior references to point to new locations
      - Consult ...
  - Do some bookkeeping for source regions

Compaction Phase (Cont.)

- New location of object x
  - Start with destination of the region containing x
  - Add size of partial object extending onto the region
  - Add sizes of live objects that precede x in the region
    - Consult the bitmap :-)
- ```
  region(x).destination() +
  region(x).partial_obj_size() +
  bitmap.live_words_in_range(region_start, x)
  ```
  ```

Compaction Phase (Cont.)

- Filling a region
  - Find the first byte destined for this region
  - Copy objects until region is full (or nothing left to copy)
  - Do some bookkeeping for source regions
    - Decrement destination count
    - If count reaches 0, region can be filled

Compaction Phase (Cont.)

- Filling a region
  - Find the first byte destined for this region
  - Copy objects until region is full (or nothing left to copy)
  - Do some bookkeeping for source regions

Compaction Phase (Cont.)

- Filling a region
  - Find the first byte destined for this region
  - Copy objects until region is full (or nothing left to copy)
  - Do some bookkeeping for source regions
- Whew!

DEMO

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Parallel Successes

- Parallelism used successfully so far
  - Parallel Scavenge
  - Concurrent Mark Sweep
  - Parallel Compaction
- Naturally, we (and you!) want more…
  - Shorter, predictable pauses—less disruption
  - Without fragmentation problems

Evaluating a New Low-latency GC

- Generational
- Parallel
- Concurrent
- Predictable
  - Pauses managed to meet specified goals
- Compacting
  - Only part of the heap at a time
  - Keeps pauses small

Evaluating a New Low-latency GC

- Generational, without fixed generations
  - Single physical space
  - Divided into “regions”
  - Young and old regions can be intermixed
    - Absence of fixed boundary allows flexibility
- Marking phase
  - Concurrent and parallel (like CMS)
  - Calculates liveness info per region
  - Much shorter remark pause than CMS

Evaluating a New Low-latency GC

- Per-region liveness info
  - Used to identify empty and mostly-empty regions
  - Empty regions—reclaimed
  - Mostly-empty regions
    - Evacuated—live objects copied to other regions
    - Then reclaimed
- All collection through copying
  - Focus on mostly-empty regions
    - Maximizes GC efficiency
  - Both young and old regions collected

Evaluating a New Low-latency GC

- Predictability
  - Model GC costs
  - Predict and schedule GC activity
- Shorter pause times
  - Through tricks!

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- Parallelism is pervasive
- Must be exploited for good performance
  - Throughput
  - Responsiveness
- Java HotSpot technology GC makes use of it today
  - In several different forms
- We can only expect more opportunities in the future

For More Information

Resources

- Ask the Experts
  - Today, 12:00 Noon—Pavilion, Booth 724
- BOF-0197
  - “Java HotSpot VM Q&A”
  - Thursday, 7:30pm
  - Moscone Center North Mtg Room 121/122
- GC Tuning Guides
  - http://java.sun.com/docs/hotspot/gc5.0/gc_tuning_5.html
  - http://java.sun.com/docs/hotspot/gc1.4.2/index.html
- Description of the GCs in the Java HotSpot VM
  - http://www.devx.com/Java/Article/21977/

Q&A

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the POWER of JAVA™

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