Parallel Garbage Collection

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Shanghai Many-core Workshop
2008-3-28

Agenda

- Quick overview on Garbage Collection
- Parallelization topics
  - Traversal of object connection graph
  - Order of object copying
  - Phases of heap compaction
  - Marking of live object
- Other GC threading topics
- Apache Harmony and GCs

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Garbage Collection: Why?

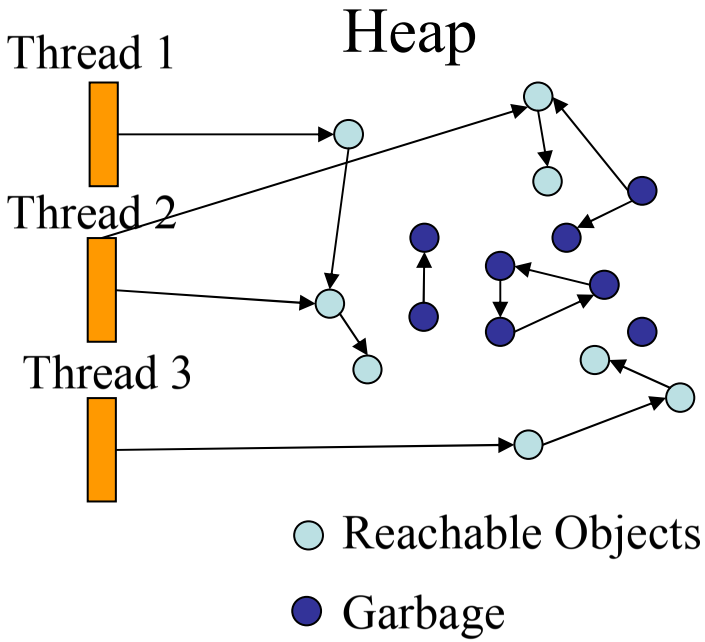
- GC is universally available in modern programming systems
  - Automatic memory management
  - Largely improves SW develop. productivity
  - Java, C#, Javascript, Ruby, etc.
- GC helps to attack memory wall & power issues
  - In the many-core era

Garbage Collection: What?

- Runtime system identifies dead objects automatically
- Known non-manual approaches
  - Runtime reference counting
    - Runtime overhead, cyclic references
  - Compiler live-range analysis
    - Limited capability
  - Runtime reachability approximation
    - This talk focus

Garbage Collection: How?

- Traverse object connection graph from application's thread context
  - Root references in:
    - Stacks
    - Registers
    - Global variables



Garbage Collection: Algorithms

- Mark-sweep
  - Trace & mark live objects, sweep dead ones
  - Non-moving
- Copy
  - Trace & copy live objects to free area
  - Require free area as copy destination
- Compact
  - Mark live objects, compact them together
  - In-place defragmentation

Key Operations in GC

- Mark-sweep
  - Trace & mark live objects, sweep dead ones
  - Non-moving
- Copy
  - Trace & copy live objects to free area
  - Require free area as copy destination
- Compact
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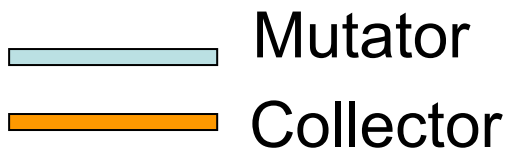
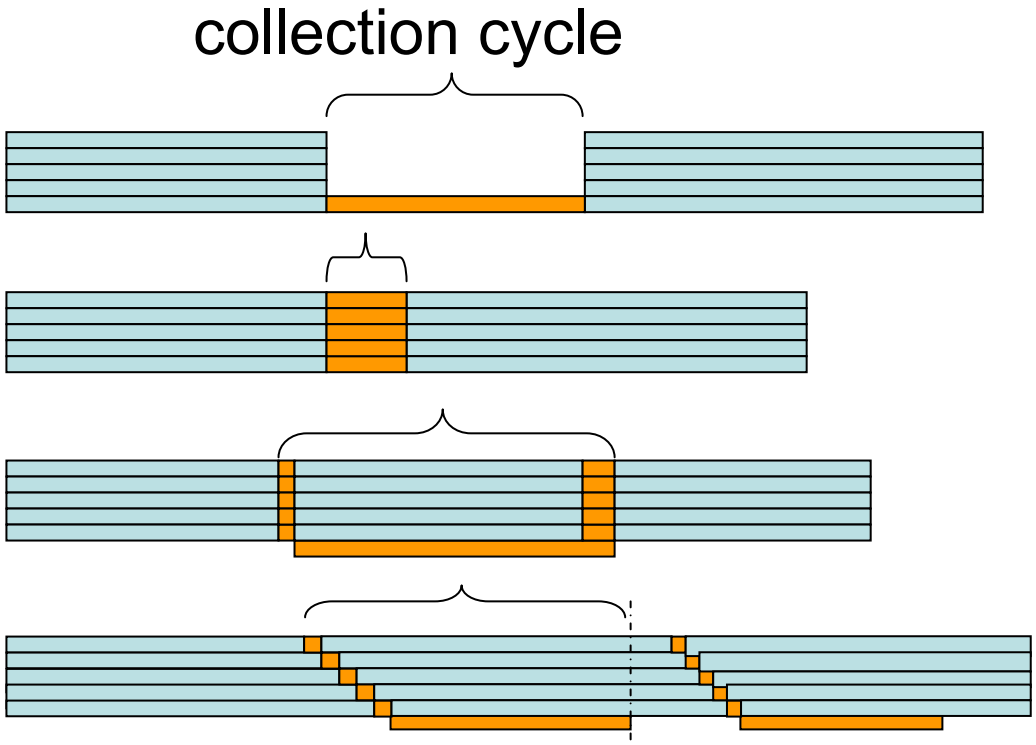
Parallelization Topics

- Next
  - Traversal of object connection graph
  - Order of object copying
  - Phases of heap compaction
  - Marking of live object

GCs We Developed

- In Apache Harmony





- GCv4.1
  Stop-the-world
- GCv5
  Parallel STW
- Tick
  Mostly concurrent
- Tick
  On-the-fly

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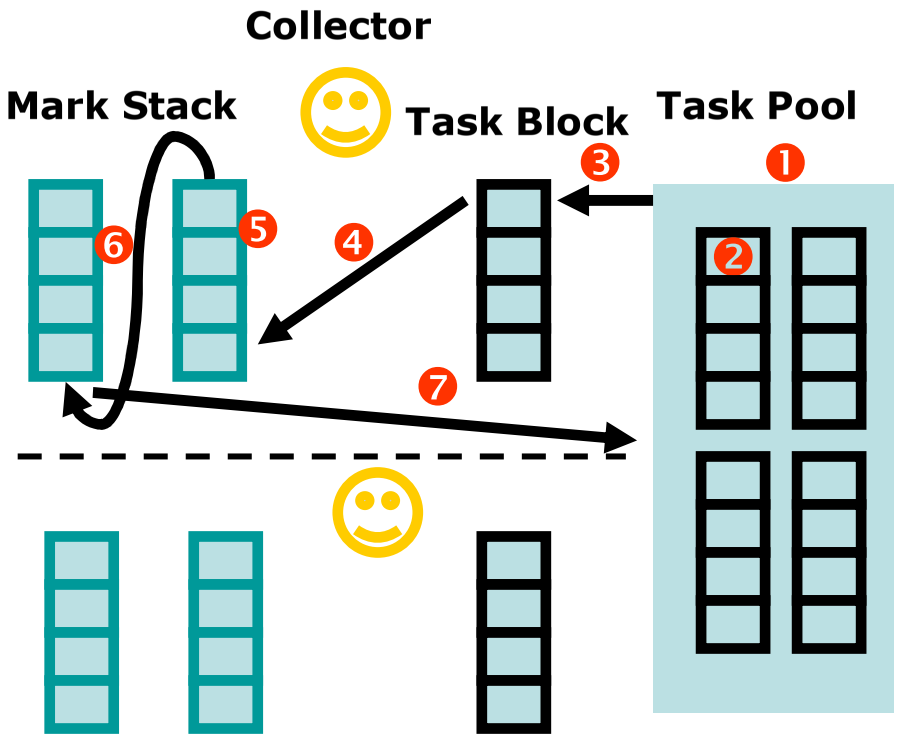
Traversal of Object Graph

- Visit all the nodes in the graph
  - Graph shape is arbitrary
  - Task (mark an object) granularity is small
  - Question: load balance among collectors
- Techniques
  - Pool sharing: share a common pool of tasks
  - Work stealing: steal tasks from other collector
  - Task pushing: push tasks to other collector

Traversal: Pool Sharing

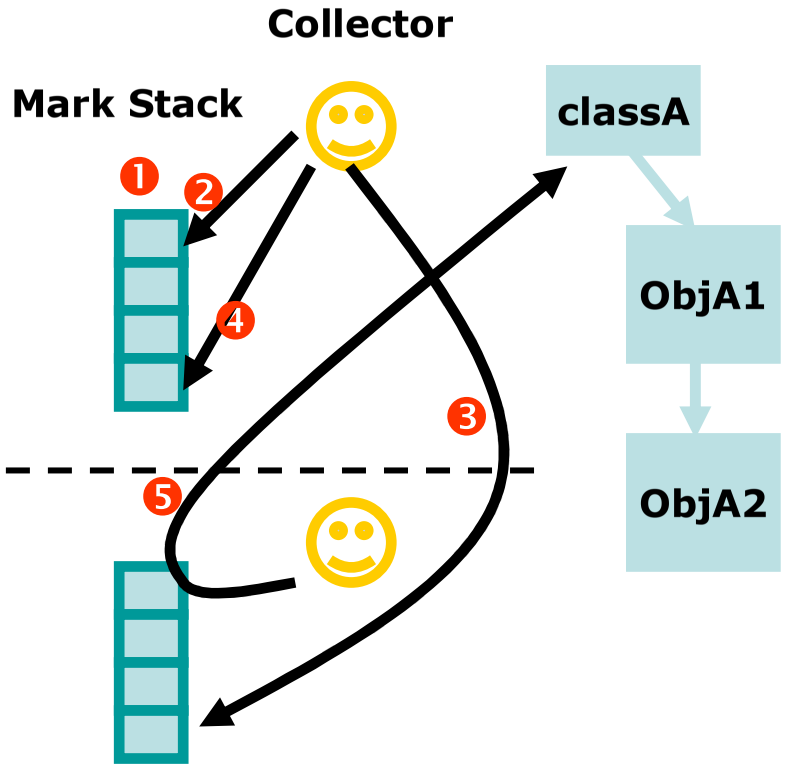
1. Shared Pool for task sharing
2. One reference is a task
3. Collector grabs task block from pool
4. Pop one task from task block, push into mark stack
5. Scan object in mark stack in DFS order
6. If stack is full, grow into another mark stack, put the full one into pool
7. If stack is empty, take another task from task block



- Block size and stack depth impact
- Need synchronization for pool access

Traversal: Work Stealing

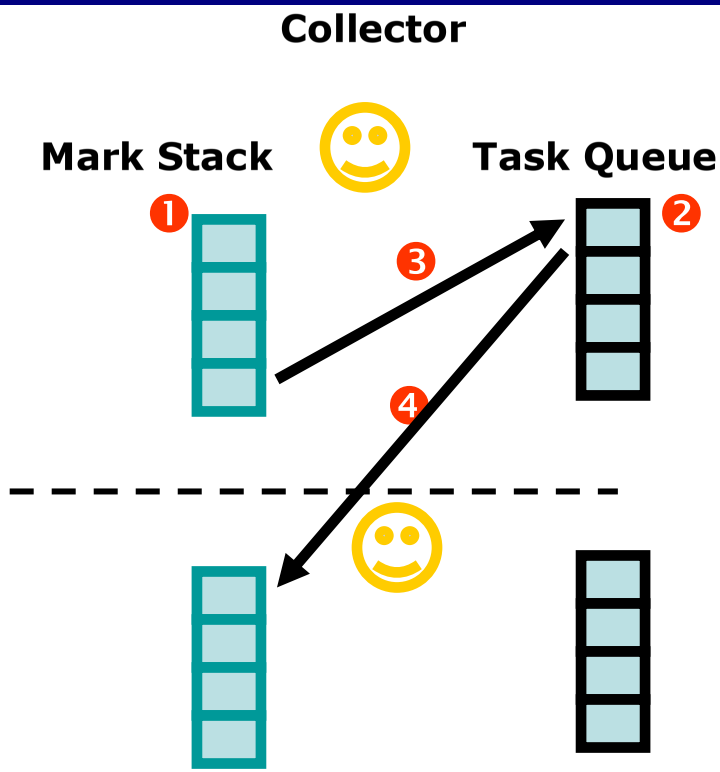
1. Each collector has a thread-local mark-stack, which initially has assigned root set references
2. Collectors operate locally on its stack without synchronization
3. If stack is empty, collector steals a task from other collector's stack's bottom
4. If stack has only one entry left, the collector need synchronization access
5. If stack is full, it links the objects into its class structure (should never happen in reality)



- Stack requires special handling when full
- Need synchronization for task stealings

Traversal: Task Pushing

1. Each collector has a thread local mark stack for local operations
2. Each collector has a list of output task queues, one for each other collector
3. When a new task is pushed into stack, the collector checks if any task queue has vacancies. If yes, drip a task from mark stack and enqueue it to task queue
4. When mark stack is empty, the collector checks if there are any entries in its input task queues. If yes, dequeue a task



- Task queue mostly is a variable
- No synchronization instruction !!

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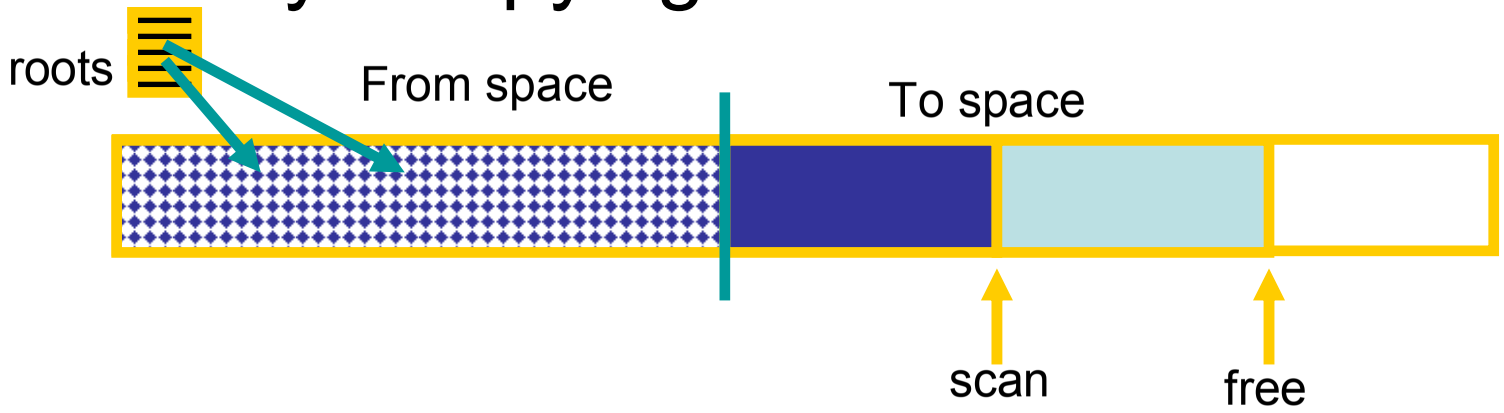
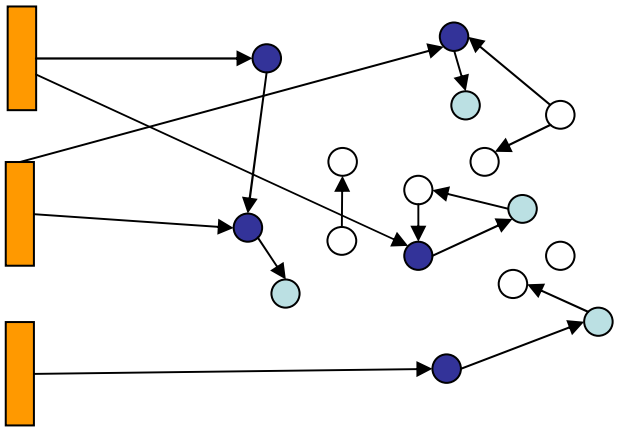
Order of Object Copying

- Object order largely impacts locality
  - Folks-belief: Allocation order has best locality
    - Maintain allocation order requires compacting
  - Question: copy order for locality
- Techniques
  - Breadth-first copy
  - Depth-first copy
  - Hierarchical order
  - Adaptive object reorder

Breadth First Order

- Cheney's copying GC

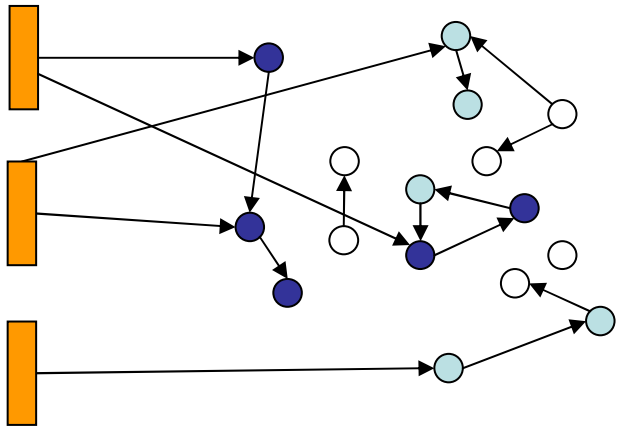




- Pros
  - No additional queue structure
- Cons
  - Probably the worst locality

Depth First Order

- Can be easily achieved with an additional mark stack
  - Stack size proportional to the deepest path

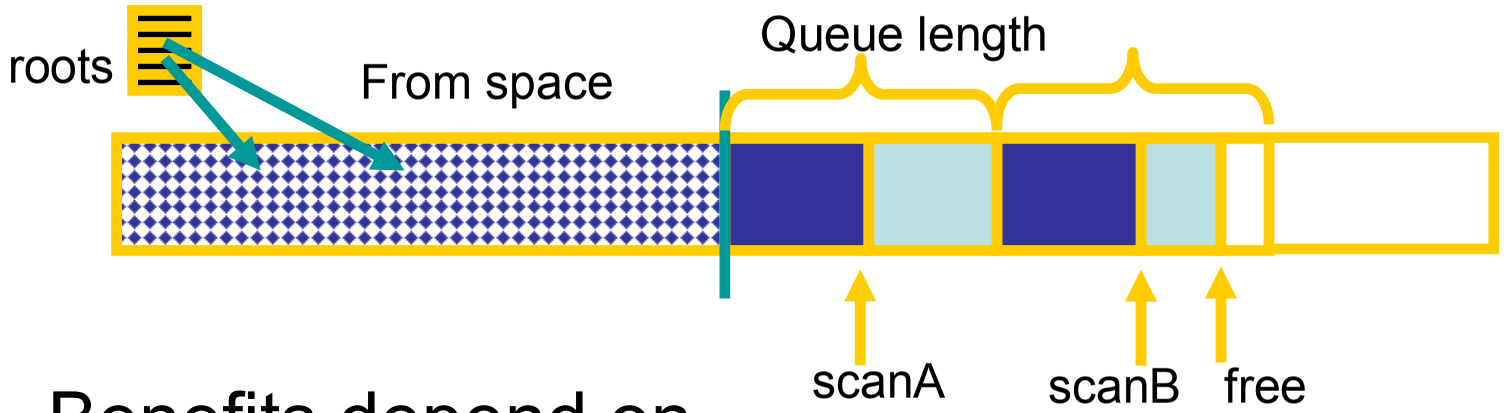


- Pros
  - Better locality
- Cons
  - Stack overhead

  * Deutsch-Schorr-Waite algorithm eliminates stack

Hierarchical Order

- Try to put the connected objects together
  - Limit the queue length of breath-first
  - Or limit the stack depth of depth-first



- Benefits depend on application behavior

Adaptive Object Reorder

- Order the objects according to VM's heuristics, e.g.,
  - Locality may relate to call graph
  - "Age locality": objects of same age tend to be accessed closely
- Pros
  - Leverage advantages of runtime
- Cons
  - Runtime overhead may cancel the benefit

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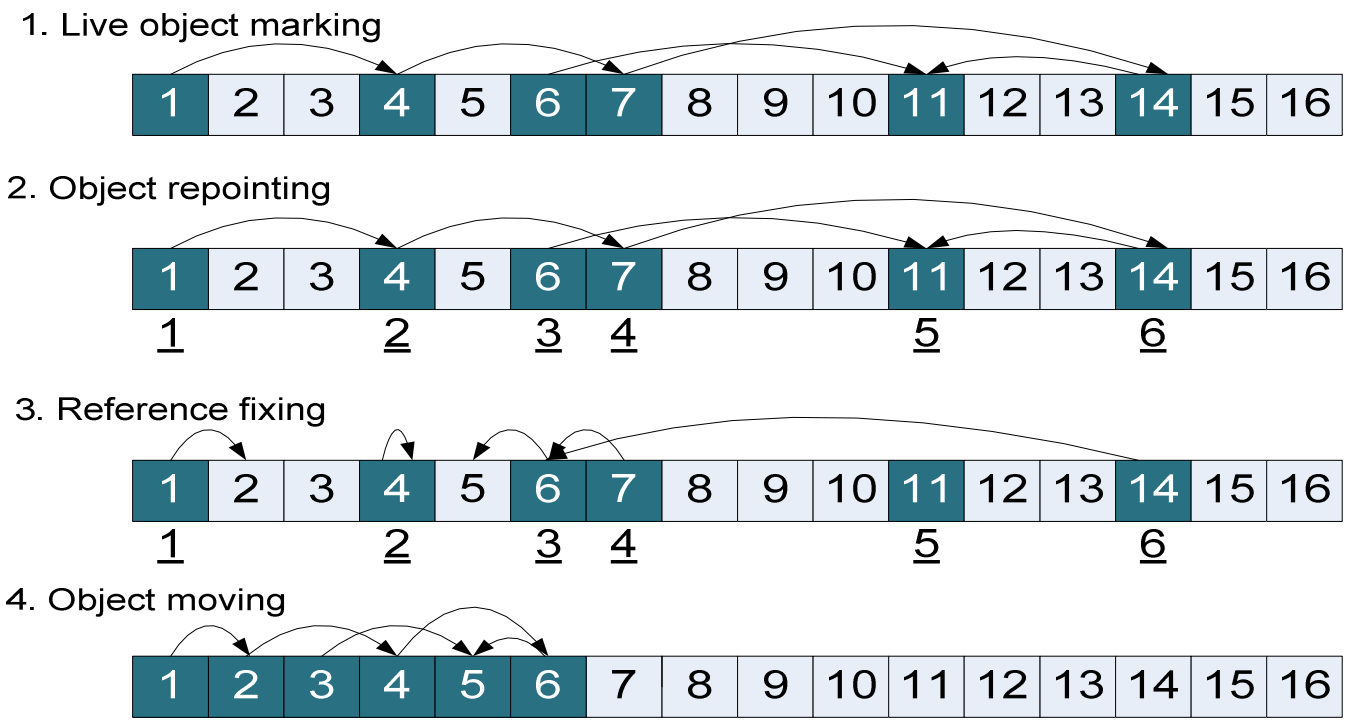
Phases of Compaction

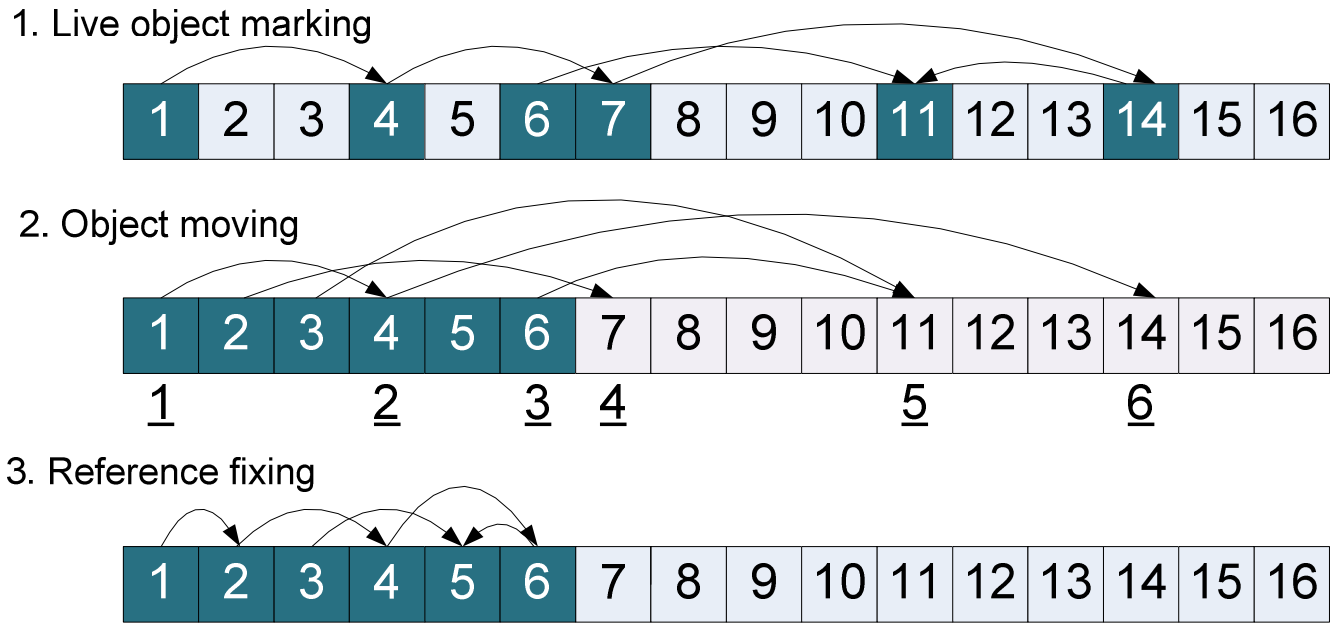
- To squeeze free areas out of the heap
  - Reserve original object order
  - Leave a single contiguous free space
- Techniques
  - Parallel LISP2 Compactor: 4 phases
  - IBM's compactor: 3 phases
  - Compressor: 2.5 phases
  - Mapping Collector: 1.5 phases

Parallel LISP2 Compactor



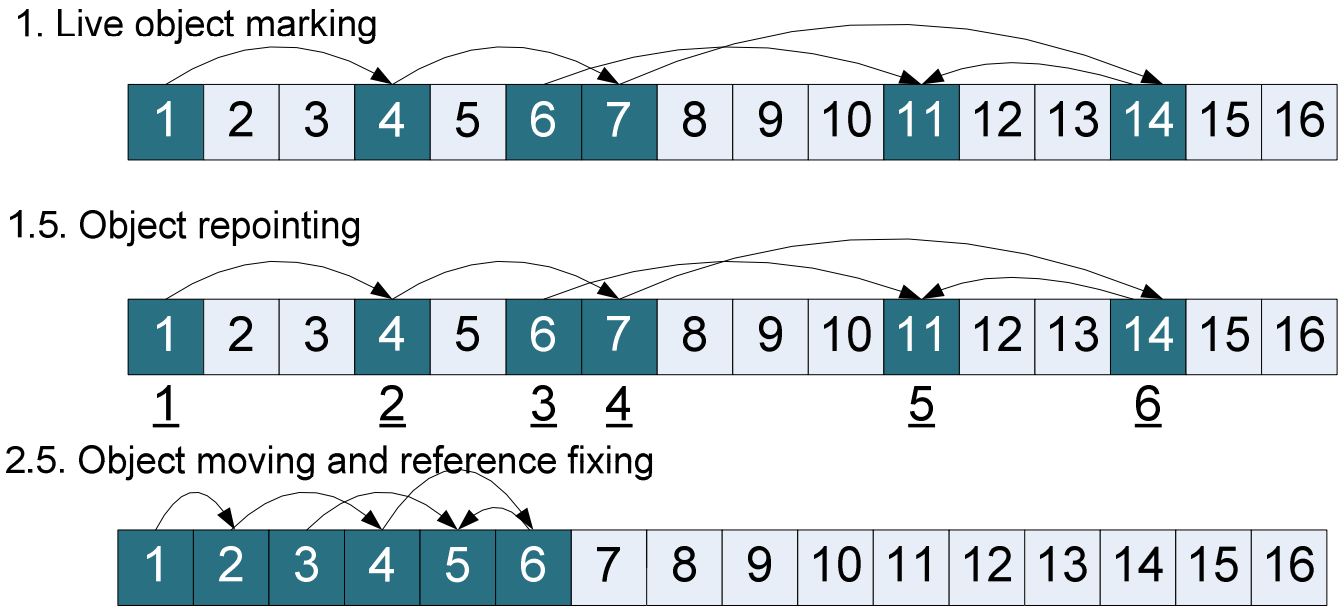
- Remember target address in object header

IBM's Compactor



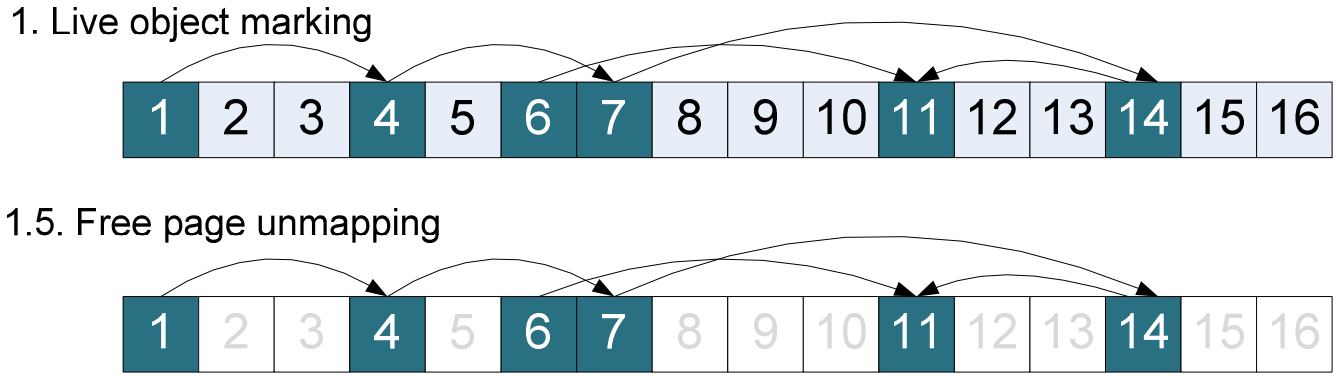
- Remember target address in offset table
  - Hence moving does not overwrite target info

Compressor



- Still, target address remembered in offset table
  - Now it is computes based on mark table
  - No touch of the object heap proper

Mapping Collector



- Check mark-bit table for free pages
  - Leverage OS virtual memory support to unmap
  - Moving is unnecessary since all are in virtual address space

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Marking of Live Objects

- Set a flag to indicate object aliveness
  - Multiple collectors may contend setting
    - Atomic operation might be used
  - Question: synchronization overhead
- Techniques
  - Mark-bit table
  - Mark-byte table
  - Object header marking
  - Section marking

Mark-bit Table

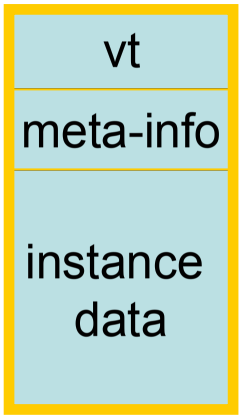
- A separate table for marking status
  - One bit in table for one word in heap
    - Word is the object alignment unit
  - 1/wordwidth of heap used for the table
- Pros
  - Small space overhead
  - Used together with other metadata
- Cons
  - Need atomic operation for bit manipulation

Mark-byte Table

- The same as Mark-bit table, but
  - One byte for one object alignment unit
  - E.g., 1/16 of heap used for the table
    - If object aligned at 16-byte boundary
- Pros
  - Atomic operation not needed
    - When byte is the minimal memory store unit
- Cons
  - Space overhead is higher

Object Header Marking

- Set the marking flag in object header
  - Usually there is a word for meta-info
- Pros
  - No atomic operation needed
- Cons
  - Iterate heap in order to find live objects
    - Slower than mark table scanning
- Marking flag design
  - Single bit or flipping bits



Section Marking

- Mark a section when an object in it is live
  - A section can have multiple objects
  - One flag is used for them, all live or dead together
- Pros
  - Combination of mark table and object marking
    - Small space overhead and no atomic operation
- Cons
  - Floating garbage and live object identification

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Other GC Threading Topics

- Thread local objects
- Finalizer processing
- Concurrent collection
- GC and transactional memory

Thread Local Object

- When object is identified as thread-local
  - Synchronization can be eliminated
  - Stack allocation
  - Scalar replacement, object inlining
- Techniques
  - Static escape analysis
  - Dynamic escape analysis (escape detection)
    - Write barrier or read barrier approach
  - Lock reservation, lazy lock

Thread Local Identification

- Static escape analysis
  - Identify life-time TLO
- Dynamic escape analysis
  - Allocation-time TLO, monitor then after
- Lock reservation
  - Not thread local, but lock local
- Lazy lock
  - Allocation-time lock local

Finalizer Processing

- Finalizer is a method
  - Invoked when an object is to be reclaimed
  - Different from C++ destructor
- Finalizers executed in separate thread(s)
  - Finalizable objects are not reclaimed yet
    - Occupy the space; finalizer may create objects
    - And mutators may keep creating new finalizables
- Question: Balance of mutators and finalizing threads

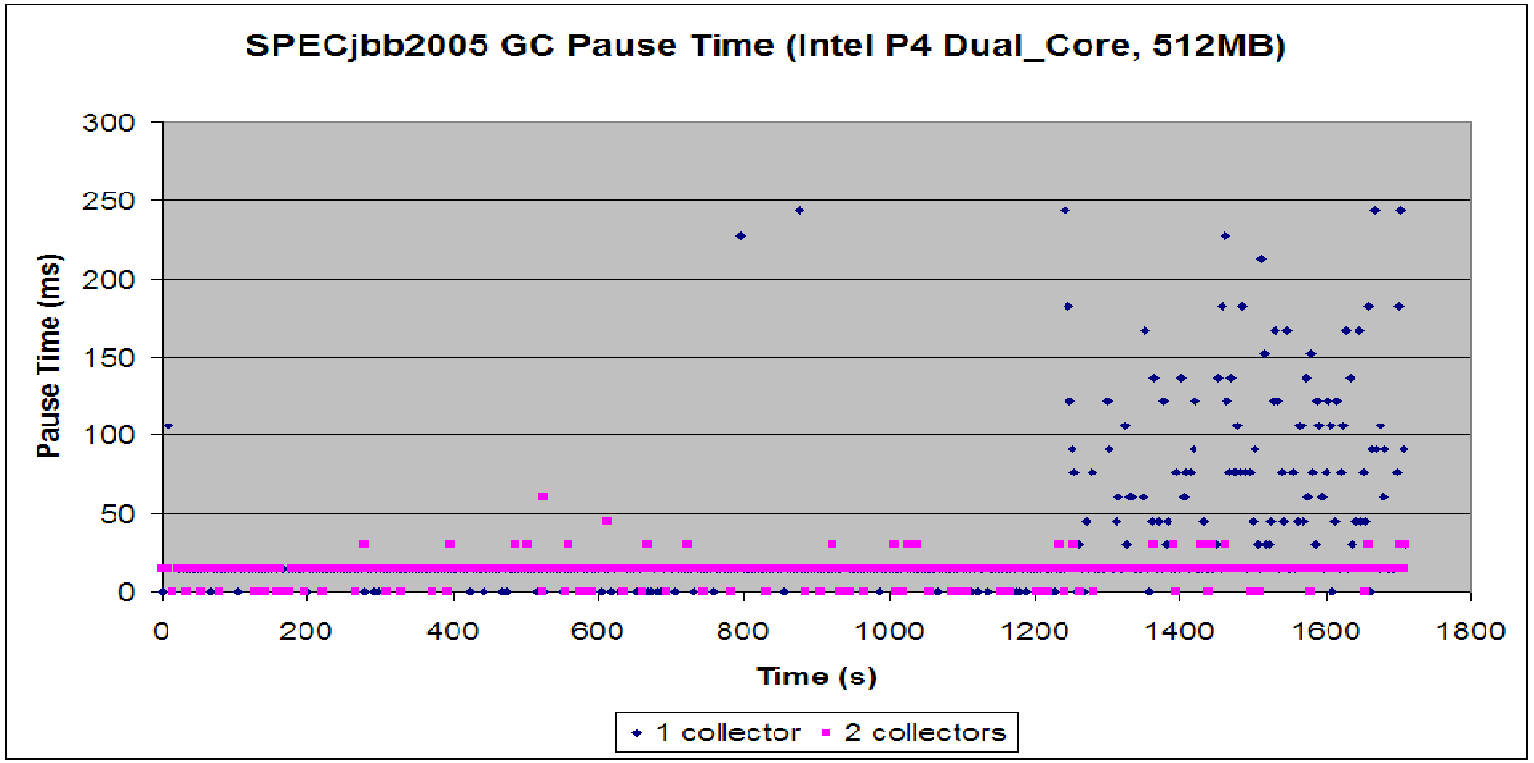
Mutator-Blocking Finalization

- When there are too many finalizers
  - Either start more finalizing threads to compete with mutators for computing resource
    - Preferred when there are idle cores
  - Or suspend guilty mutators until finalizers number drops below a threshold
    - Preferred when cores are all busy

Concurrent collection

- Collecting garbage while application runs
  - For low-pause time (or pauseless)
- Collect with separate collector threads
  - Utilize idle cores
  - Normally single thread is adequate
    - To use least computing resource
    - But if collect slowly, mutators wait for free space
- Question: Balance of collection rate and allocation rate

Collectors Work-on-Demand



- Start more collectors when needed adaptively

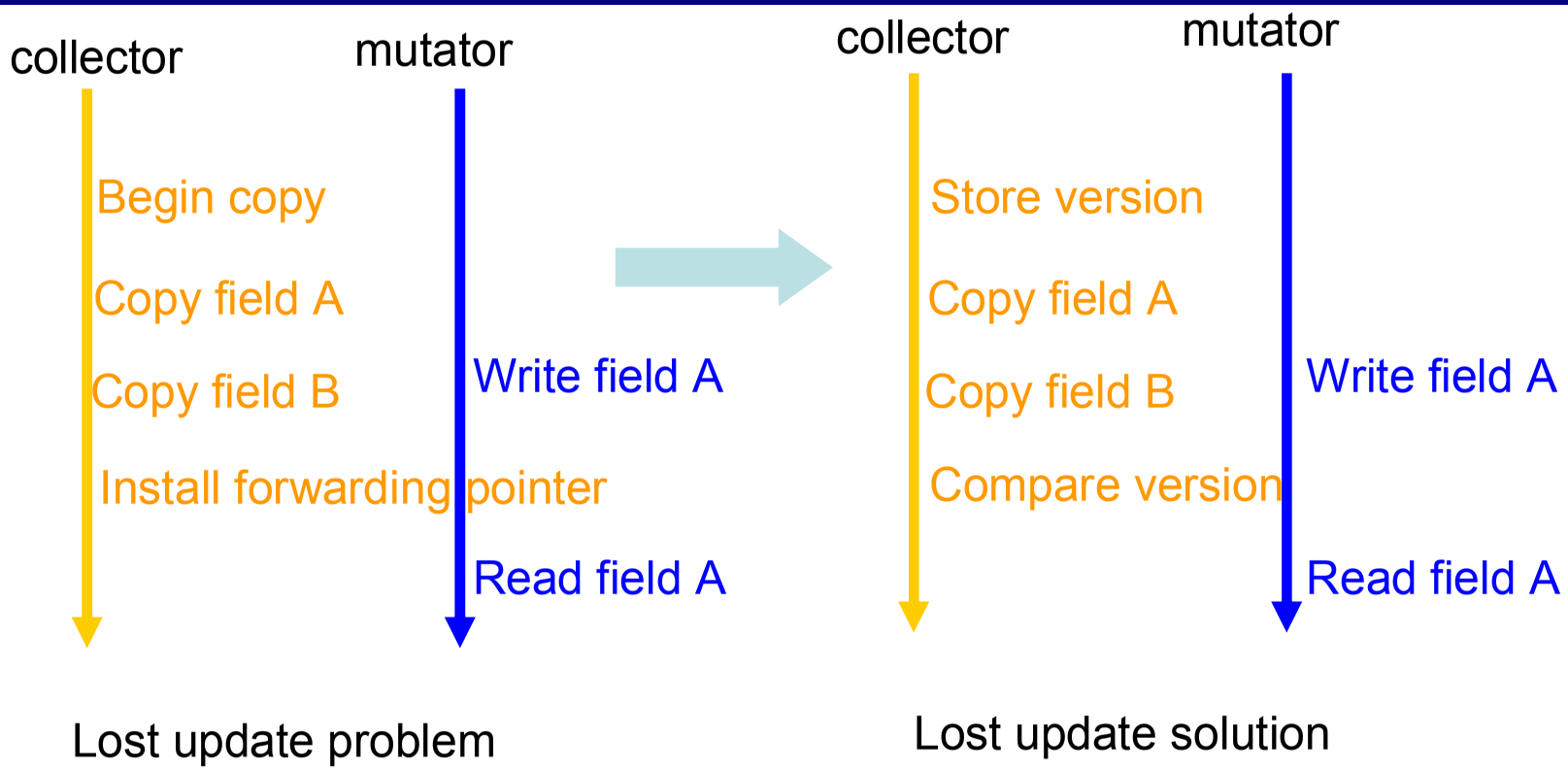
GC and Transactional Memory

	memory management	**concurrency**
correctness	dangling pointers	races
performance	space exhaustion	deadlock
automation	garbage collection	transactional memory
new objects	nursery data	thread-local data

Transactional memory is to shared-memory concurrency as *garbage collection is to memory management*

- Dan Grossman, Software Transactions: Programming-Languages Perspective. 2008

Concurrent Copying GC on TM



- Phil McGachey, Ali-Reza Adl-Tabatabai, Richard L. Hudson, Vijay Menon, Bratin Saha and Tatiana Shpeisman, Concurrent GC Leveraging Transactional Memory, PPoPP2008

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Apache Harmony

- Primary goal: full JavaSE implementation
  - Class library, competitive VMs, JDK toolset
  - Founded in Apache Incubator in May 2005
  - Became Apache project in Oct 2006
- Facts today
  - 27 committers, 30 commits weekly (currently)
  - 250 messages weekly in mailing list
  - 150 downloads weekly

Harmony DRLVM

- The current default VM of Harmony
- Components
  - Two JIT compilers: fast and optimizing
  - Several GCs: parallel/concurrent
  - Other features: JVMTI, etc.
- Targets
  - Robustness, performance, and flexibility
  - Server and desktop
  - Product-ready

DRLVM Modularity Principles

- Modularity
  - Well-defined modules and interfaces.
- Pluggability
  - Module implementations replicable
- Consistency
  - Interfaces are consistent across platforms.
- Performance
  - Modularity without scarifying performance

Harmony GC Implementations

- GC algorithms
  - Copy: semi-space, partial-forward
  - Compact: sliding-compact, moving-compact
  - Mark-sweep
- And their variants
  - Generational and non-generational
  - Parallel stop-the-world and concurrent
- Modular design enables GC research

Summary

- GC is becoming universal in modern programming systems
  - Important component for many-core
- Parallelization and threading issues in GC
  - Load balance, locality, atomic operation overhead, concurrency, etc.
- Just starting…
  - JIT assistance, OS interaction, HW supports, programming model changes, power, etc.

Thanks! And Questions?

http://harmony.apache.org