Algorithms for Dynamic Memory Management (236780)

Lecture 6

Lecturer: Erez Petrank

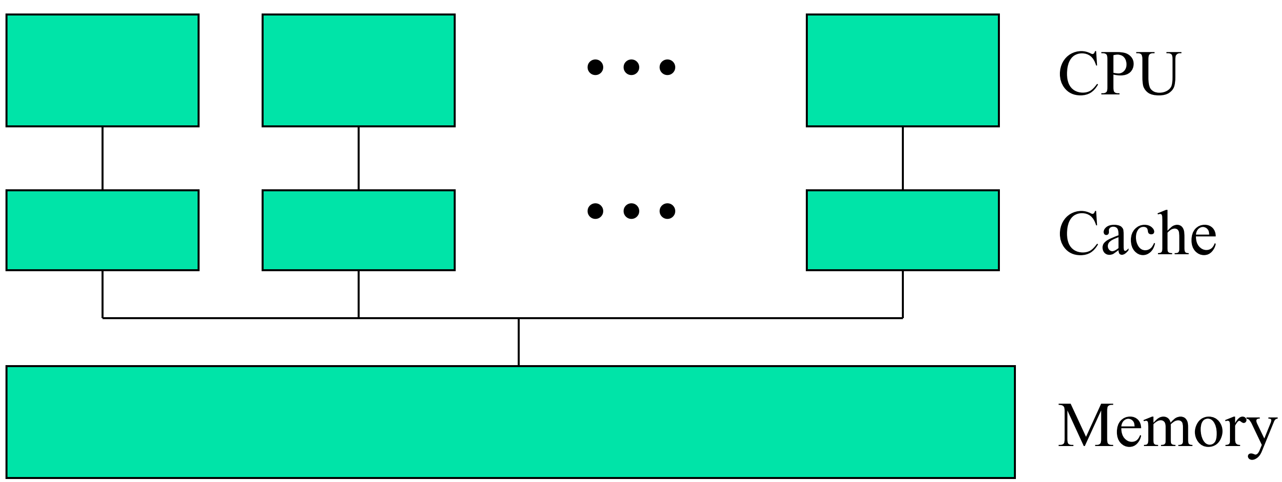
Topics last week

- Concurrent garbage colleciton:
- Dijkstra,
- DLG

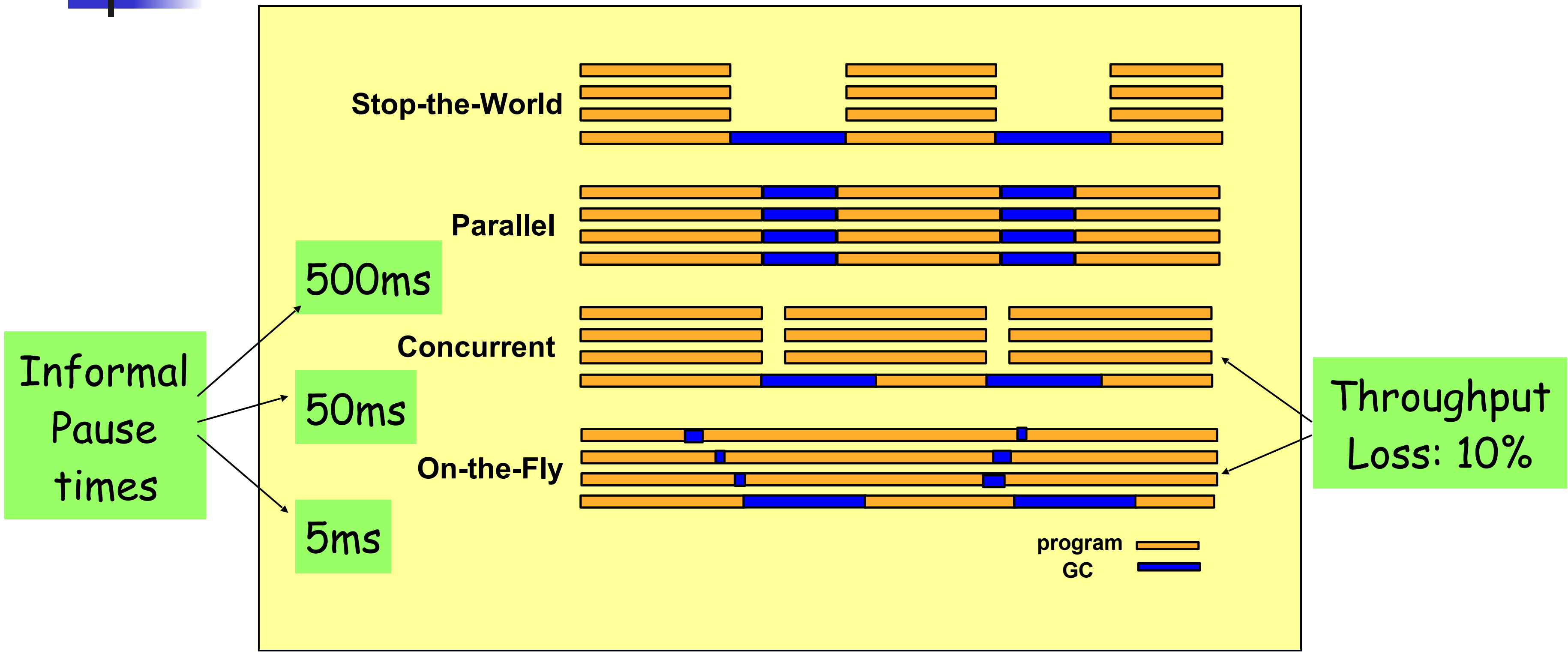
Concurrent Garbage Collection

Platfrom in Mind

Strong machines (srevers): Symmetric MultiProcessing (SMP)
shared-memory, multiprocessor



Terminology



Next

- Mostly concurrent: IBM's implementation

- Mostly Concurrent collector improvements.
  - An algorithmic approach
- Endo & Taura's idea on shortening pause times
- If time allows:
  - Snapshot copy-on-write
  - Parallel GC

Mostly Concurrent Garbage Collection

[Boehm-Demers-Shenker 1991]

[Printezis-Detlefs 2000]

[Endo-Taura 2002]

[Barabash, Ben-Yitzhak, Goft, Kolodner, Leikehman, Ossia, Owshanko, Petrank 2005]

Recall Motivation

- Garbage collection costs:
  - Throughput
  - Pause lengths
- The goal: reduce pause times with a small reduction in throughput.
- Idea: run (most of the) collection concurrently with mutators.

Recall Difficulty

- The heap changes during collection.
- The main problem is that marked (black) objects may point to unmarked (white) objects.

- Solution: trace again all marked objects that were modified by the program.
- Use a card table to record modified objects (actually, cards).

Mostly-concurrent GC

- Trace: run marking concurrently.
  - Write barrier: when a pointer is modified, its card is marked.
- Card cleaning: for each dirty card:
  - Clear dirty bit
  - Re-trace from all marked objects on the card.
- Stop mutators
- Repeat card cleaning while program halted.
- Resume mutators
- Sweep.

More Issues

- New objects are created black (marked).
- Liveness: Objects unreachable in the beginning of the collection are guaranteed to be reclaimed.
- Floating garbage: Objects that become unreachable during the collection might not be collected.
- Trade-offs: It is possible to do more phases of card cleaning.

Conclusion

- This collector does most of the work concurrently with the program.
- It is stopped for a short while in the end to clear (and scan) all dirty cards.
- Properties:
  - Short pauses, simple write-barrier
  - Overhead: write barrier, repeated scanning of dirty cards.

Parallel, Incremental, and Mostly Concurrent GC

- A specific memory manager
- IBM Production JVM since ~2002
- Published in PLDI'02, OOPSLA'03, TOPLAS'05

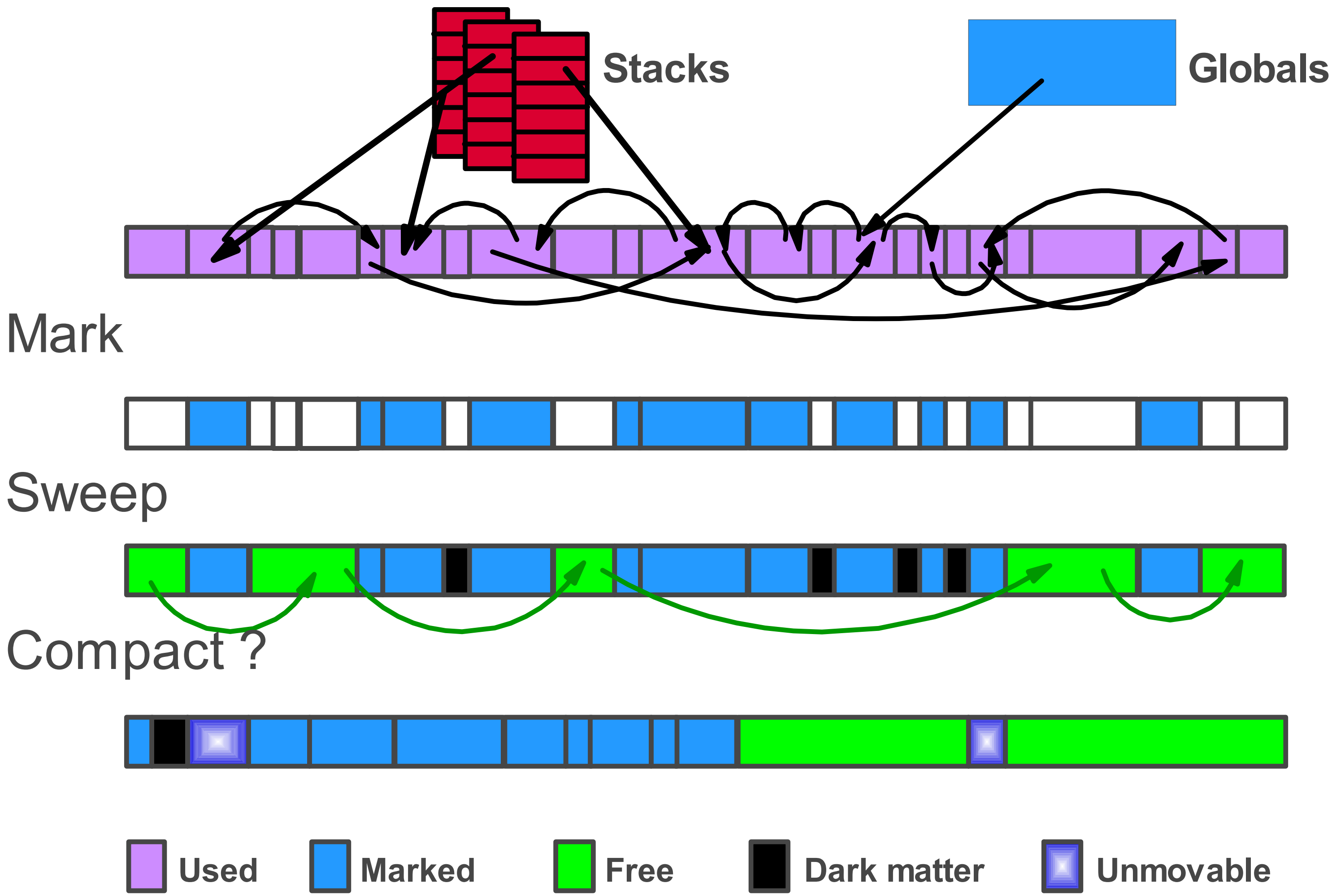
Motivation (Industry Style)

- Modern SMP servers introduce
  - Higher level of true parallelism
  - Multi-gigabyte heaps
  - Multi-threaded applications which must ensure fast response time
- New demands from Garbage Collection (GC)
  - Short pause time on large heaps
    - Not “real-time”, but restricted below a given limit
  - Minimal throughput hit
  - Scalability on multi-processor hardware
  - Efficient algorithms for weak ordering hardware
    - We will not talk about this....

Mark-Sweep-Compact GC

- The collector is mark-sweep-compact.
- Mark - traces all reachable (live) objects in heap
- Sweep - Create a list of free chunks
- Compact
  - Move the live objects, to create bigger free chunks
  - Usually very long.

The General Picture

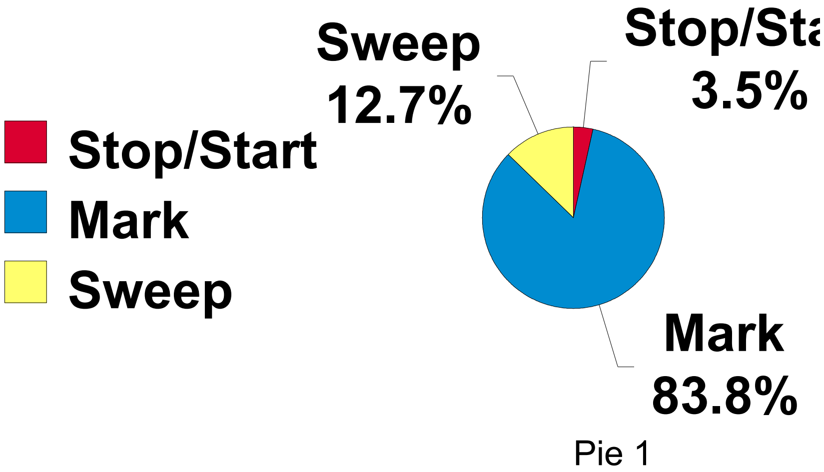


Bitwise Sweep

- A major overhead of sweep is finding & freeing each chunk of 0's in the mark-bit table.
- Solution: free only large chunks of objects.
  - Sweep uses only full zero words (fast search).
  - When found – free the entire chunk of zeros (not only the space presented by the zero word).
- Advantage: looking for a zero **word** is fast.
- Disadvantage: looses some space (but only small chunks).

The Concurrent Collection Costs

- Stop-the-world may get to seconds (at 2004)
- Cost of mark phase dominant



The Mostly Concurrent Collection

- Tracing done while mutator threads are active
- Mutator runs card marking: “dirties” cards that are modified.
- Card cleaning runs concurrently.
- Finally, a short stop-the-world phase
  - Last clean and resulting tracing
  - Sweep (or ever better, lazy sweep)

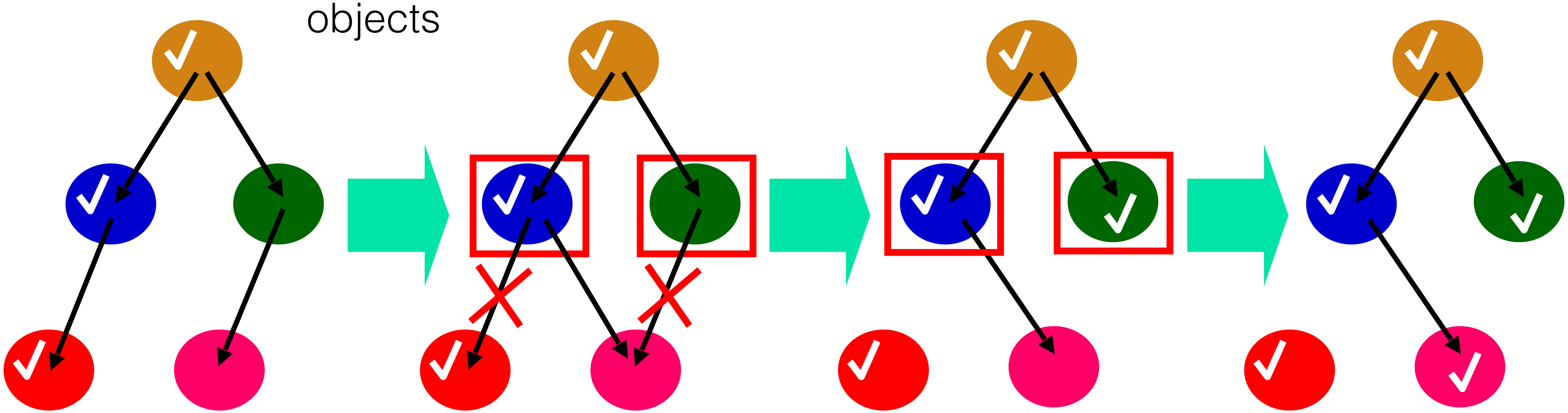
The Write Barrier and Object “cleaning” Solution

Tracer:
Marks and traces

Java Mutator:
Modifies Blue and Green objects
Write barrier on objects

Tracer:
Traces rest of graph

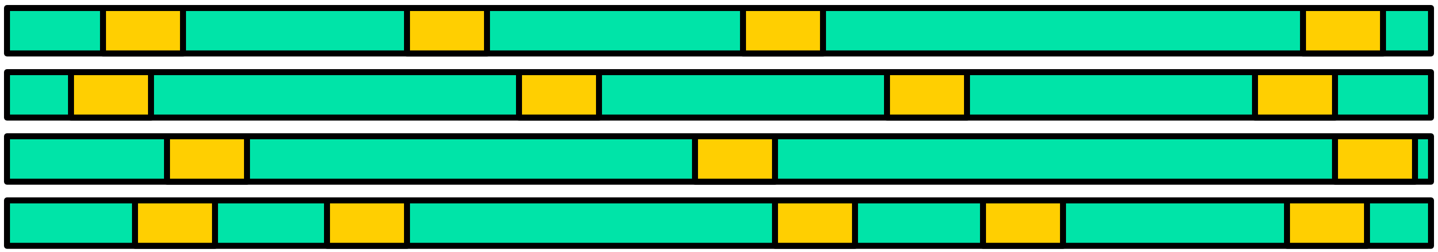
Tracer:
<u>Clean</u> blue object



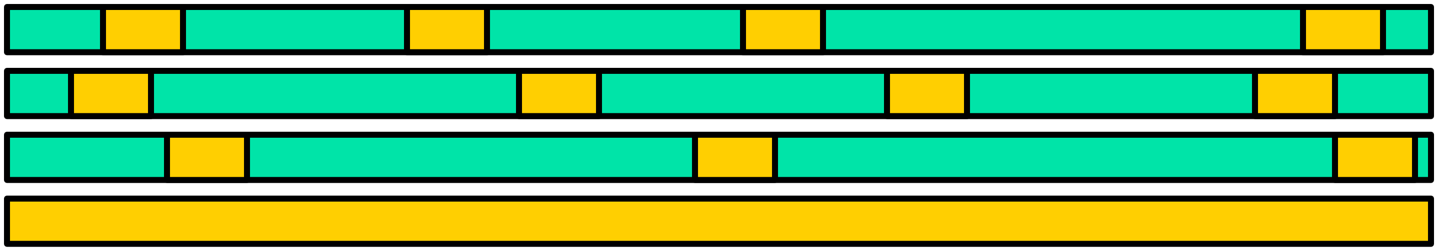
Who Runs the Collection ?

- Tracing done incrementally by the mutator threads, when allocating. (Recall Baker's copying collector.)
- Incremental and parallel: several threads may run their incremental share of the collection in parallel.
- Finally, add some concurrency to the picture.

Incremental and parallel



Incremental, Concurrent and Parallel:



Phases of The Collector

- Concurrent phase
  - Reset the mark bits and the dirty cards table
  - Trace all reachable objects (incremental, parallel, concurrent).
    - Write Barrier records dirties cards in a **card table.**
  - A single card cleaning pass: in each dirty card, retrace all marked objects
- Final stop-the-world phase
  - Root scanning and final card cleaning pass
  - Tracing of all additional objects
  - Parallel sweep (To be replaced by concurrent sweep).

Write Barrier Implementation

- Activated by the JVM, on each reference change done in Java.
- Cards are 512 bytes; card table has a bit for each card.
- Note that card cleaning may happen anytime
  - Including in the middle of write barrier execution!
- Therefore a race is possible…

Write Barrier Race

- A race between card cleaning and write barrier.
- Naïve write barrier:
- Obj1.a = Obj2
    1. Set Obj1.a to Obj2
    2. Dirty the entry of Obj1 in the card table
- If collector finishes between 1 and 2, it will not see the dirty card!
- Switching order does not help since card cleaning can happen between 1 and 2, erasing the dirty mark.

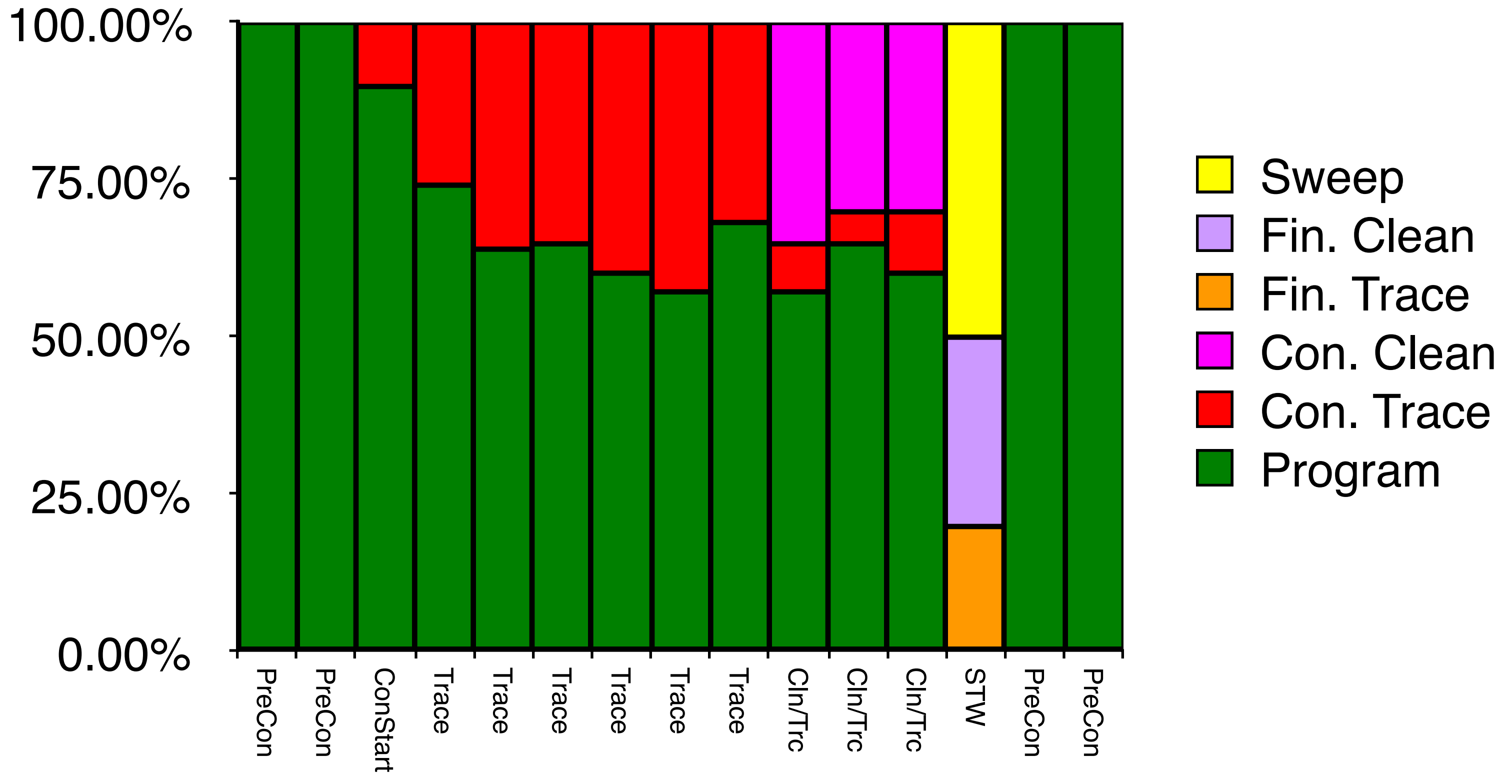
Avoiding the Race

- Extra registration in a local variable.
- Obj1.a = Obj2
  1. Store Obj2 in a root (guarantied to be reachable)
  2. Set Obj1.a to Obj2
  3. Dirty the entry of Obj1 in the card table
  4. Remove Obj2 from root
- This also solves sensitivity to memory coherence, not discussed in this course.

Outline

- Introduction
- Principles of concurrent collector
- Dynamically controlling the concurrent work
- Parallel load balancing mechanism
- Coding issues
- Results (highlights)
- Algorithmic Improvement
  - Results

CPU distribution In Mostly Concurrent GC



The Problem of Punctual termination

- Stop-the-world collection starts when heap is full
- Mostly concurrent aims at completing the marking **exactly** when heap becomes full
  - Completing GC late - program gets stalled.
  - Completing GC early - we get more garbage collection cycles and pay an efficiency cost.
- Solution: adaptive incremental work.

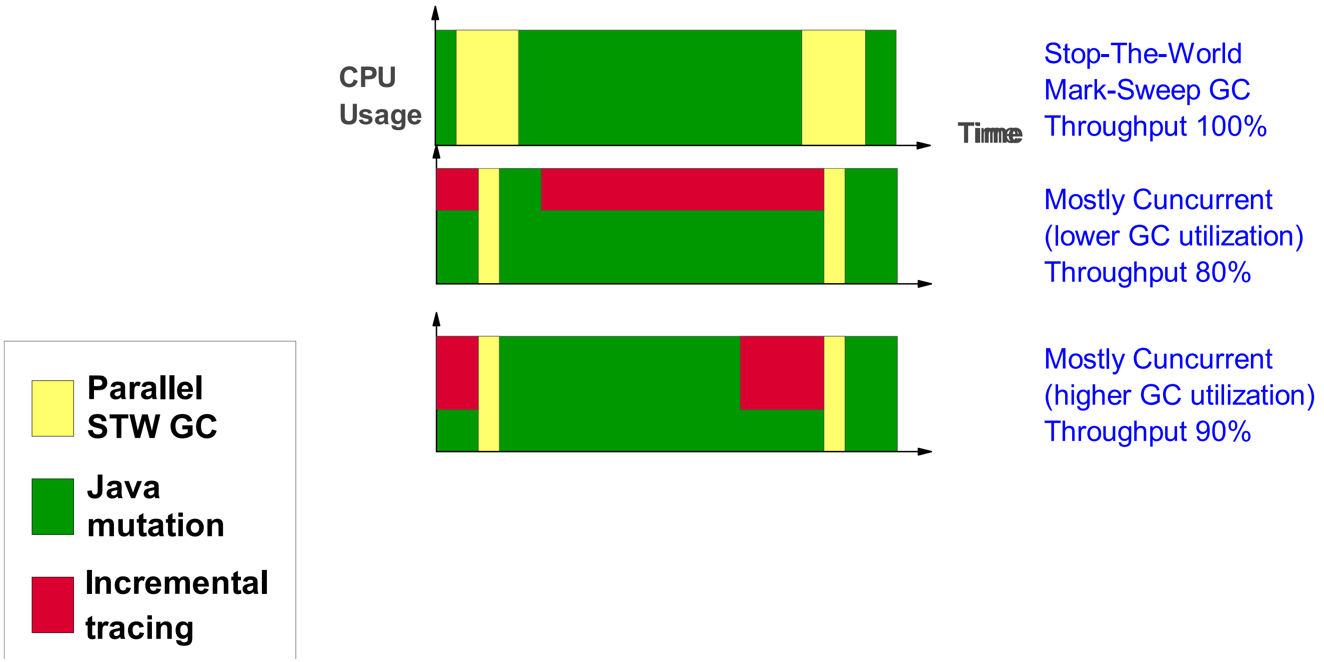
Advantage of Incremental Work

- We can influence collection speed by choosing how much collection to do with each allocation.
- The ratio of collector work to program allocation is denoted tracing rate.
  - tracing rate = work to do per allocated byte.
  - Goal: tracing rate = work-to-be-done/free-space.
  - Implies that tracing terminates on time.
- Estimate remaining work and free space, tune tracing rate.

Impact of Tracing Rate

- On a low tracing rate
  - GC takes a long time
  - Many cards get dirty
  - Repeated tracing takes more time
- GC is less efficient, program gets less CPU overall.
- But: program gets more CPU percentage.
- Therefore, we let the user specify an initial tracing rate.
- Start a collection when: estimated work on live objects > free×TR.

Behavior Patterns



JVM Utilization and Performance

with Mark-Sweep GC and Mostly Concurrent GC

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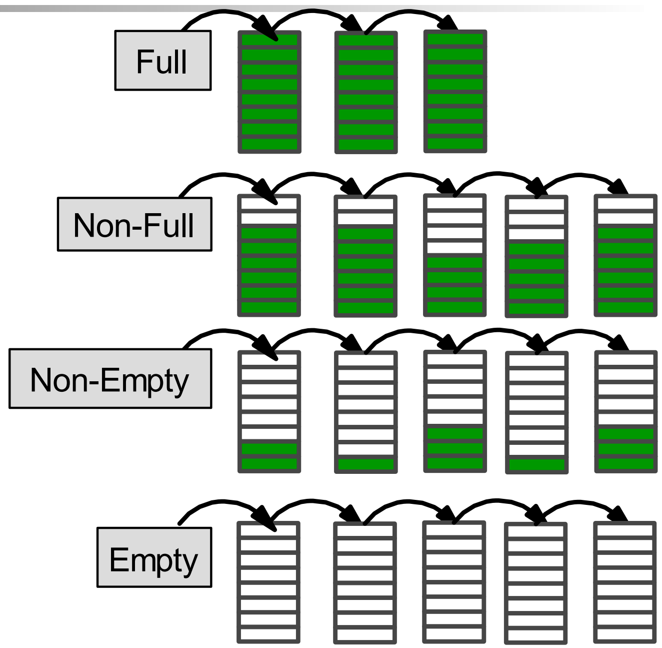
Load Balancing Goal

- Avoid idle time
- Efficient synchronization
- Simple termination detection.

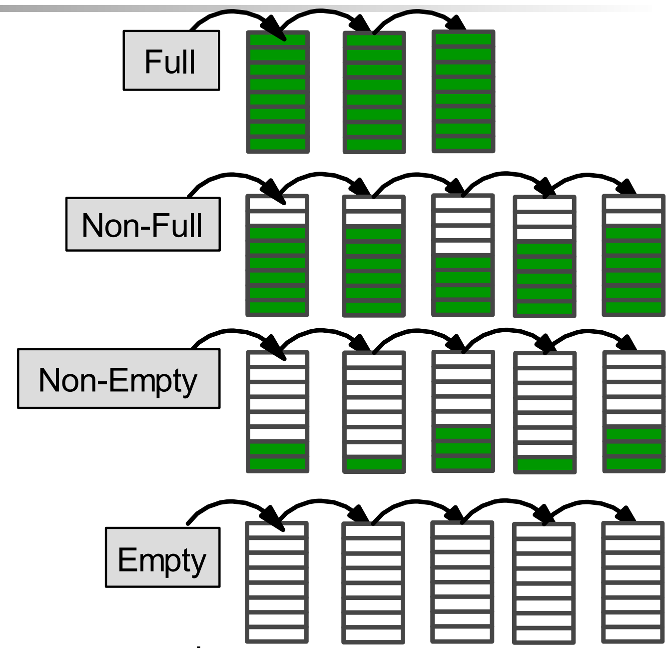
- Small tasks —> good load balancing
- Large tasks —> low synchronization costs.
- Tasks = list of objects (pointers) to traverse.

Work Packets

- Separate mark-stack into smaller work packets.
- Obtain a packet using fine-grained synchronization (compare-and-swap)
- Group packets according to occupancy.



Work Packets



- Each thread keeps an input packets and an output packet.
- Pop an object from input work-packet.
- Mark children and push to output work-packet.
- An empty input packet is returned to the empty-packets pool.
- Try to obtain as full as possible new input packet.
- A full output packet is returned to the “full” pool.
- Get as empty as possible new output packet.

Advantages of WorkPackets

- Easy work distribution
- Packet size determines task size
- Simple detection of termination (all packets in empty list)
- Good performance in practice.

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Concurrent Code is Difficult to Write Debug and Maintain

- Races between concurrent tracing and program
- Races between concurrent tracers
- Debug version cannot reproduce Release bugs
- Problems surface only occasionally
- Behavior is machine dependent

About 40% verification code

- Sanity checks
  - Asserts, consistency checks
- Logging of collection activity, state, and history
  - Shadow heap, for tracing history
  - Shadow card table, for card state and treatment
  - Code to use the above for printing detailed information.

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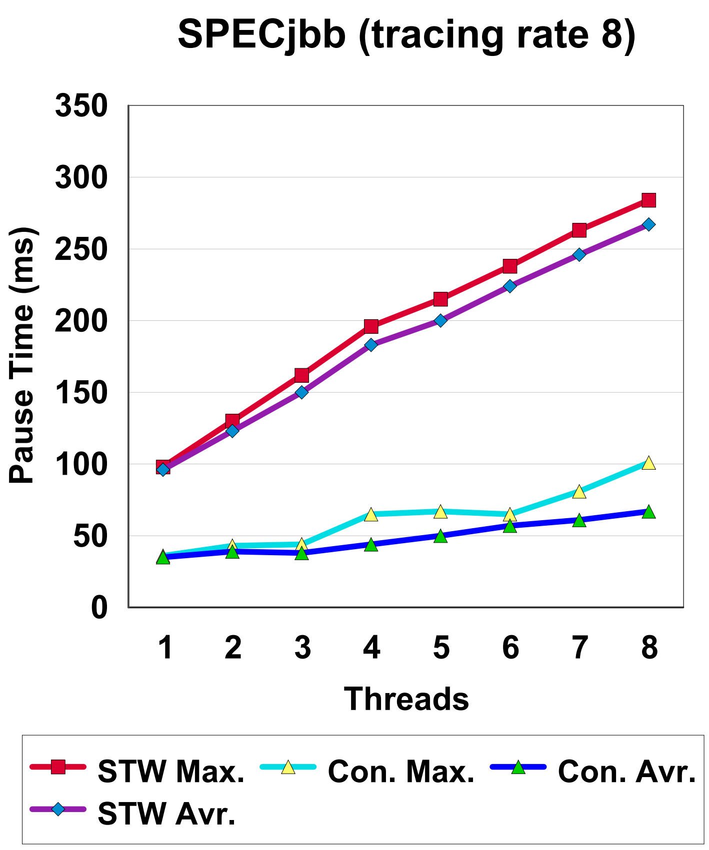
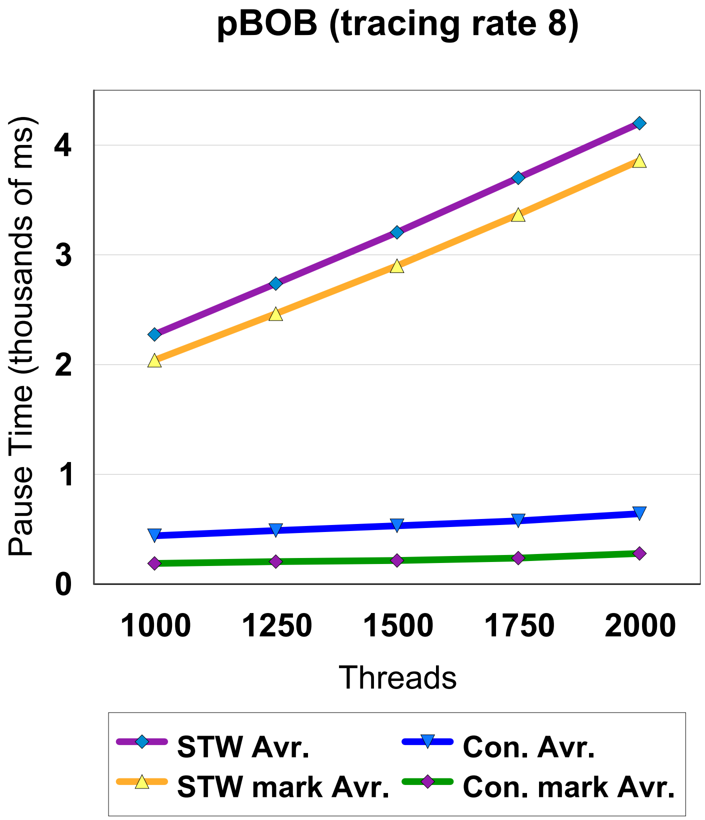
Comparison with STW GC

- Compared to STW MSC
  - Using IBM's production level JVM
  - 4-way machines
  - NT, AIX and IA64
- Mostly testing SPECjbb
  - heap size: 60% live objects
- Pause time cut by 75%
- Mark time by 86%.
  - Sweep become dominant
- Throughput hit of 10%



Comparison with STW GC (cont.)

- Also testing pBOB
  - IBM internal benchmark
  - Fit for 2.5 GB heap, with
- Low CPU utilization
  - Many threads
  - Typical to modern server Apps.



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Algorithm Revisited

- [Barabash-Ossia-Petrank 2003]
- Two simple algorithmic improvements.

The Repetitive Work Problem

- An observation:
  - Suppose a card is dirtied.
  - Reachable objects on this card are marked and traced by the collector.
  - All these objects are later traced again during card cleaning.
  - Outcome: repeated tracing
- First Improvement: Don’t trace through dirty cards

Moreover …

- On typical benchmarks:
  - Specific “hot” objects get modified frequently.
  - (Almost) all hot objects reside on dirty cards.
  - They point to objects that become unreachable later.
  - Since we trace these hot objects twice, we increase work and floating garbage.
- Not tracing through dirty cards avoids this waste.

Don’t Trace Through Dirty Cards

- While tracing, do not scan an object on a dirty card.
- Advantages
  - Less (repeated) tracing work
  - Reduced floating garbage
- Thus, substantial throughput improvements
- Disadvantage: increased pause time

Timing of Card Dirtying

- Observation
  - Dirtying a card tells us that previous tracing does not suffice.
  - No need to dirty a card if nothing was traced on it.
- Second Improvement: Undirty cards with no traced objects
  - Undirtying by scanning cards
  - Undirtying by checking local allocation caches

Undirtying via Scanning

- Undirtying periodically on the whole card table
  - Uses a second “traced” card table.
  - The card is marked when first object on it is traced.
- During the scan: undirty any card with no traced objects
  - Very effective in undirtying cards (cuts cleaning by 65%)
  - Scan imposes a cost.
- Frequency is a parameter:
  - Frequent scans: increases chances of catching cards before their objects are traced, but increase overhead

Local Allocation Caches

- Local allocation caches are used by various modern JVMs
- The idea: each program thread obtains an “allocation cache” on which it allocates small objects.
- The benefit for multithreaded program:
  - No synchronization for small allocations.
  - Better locality

Undirtying via Local Allocation Caches

- Typically, newly allocated objects are immediately initialized, thus their cards are typically dirty.
- On the other hand, new objects are usually not traced immediately after creation.
- Attempt to undirty shortly after allocating new objects.
- Collector: don’t allow tracing on allocation caches
  - if needed, put the relevant objects in a buffer to be traced later. This hardly ever happens
- Mutator: after finishing allocation on a local cache, undirty all included pages.
- Cuts the amount of dirty cards by more than 35%, at (almost) no cost.

Undirdy Cards with No Traced Objects

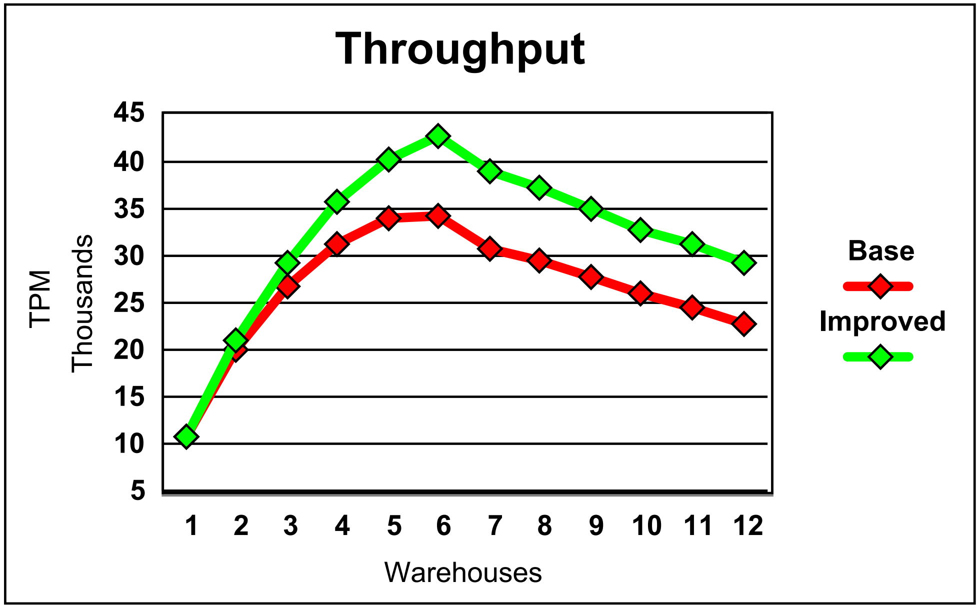
- Advantages
  - Reduces the work on scanning dirty cards.
  - This reduces the final stop-the-world phase.
  - Thus, significant impact on pauses.
- Disadvantages
  - Time overhead.

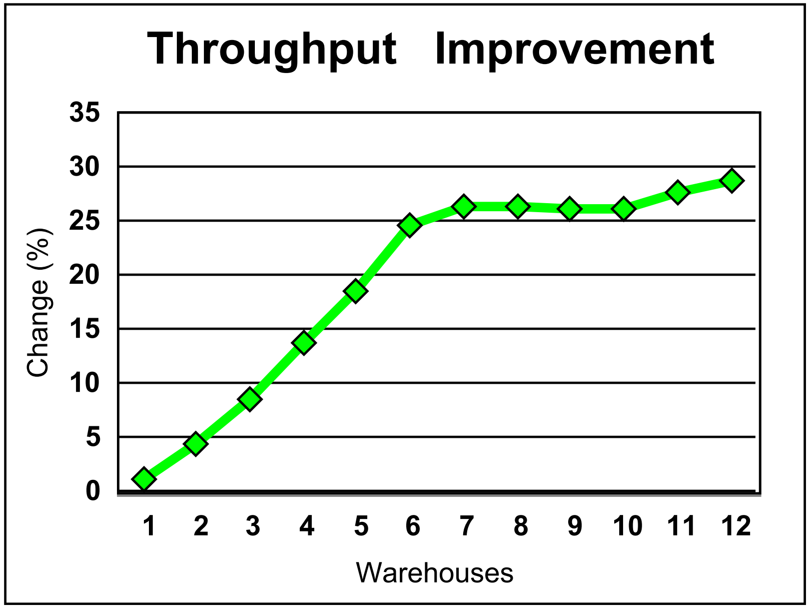
Implementation and Tests

- Implementation on top of the mostly concurrent collector that is part of the IBM production JVM 1.4.0.
- Platforms: tested on both an IBM 6-way pSeries server and an IBM 4-way Netfinity server
- Benchmarks: the SPECjbb2000 benchmark and the SPECjvm98 benchmark suite
- Measurements: performance of the base mostly concurrent collector vs. the improved version

Results - Throughput Improvement

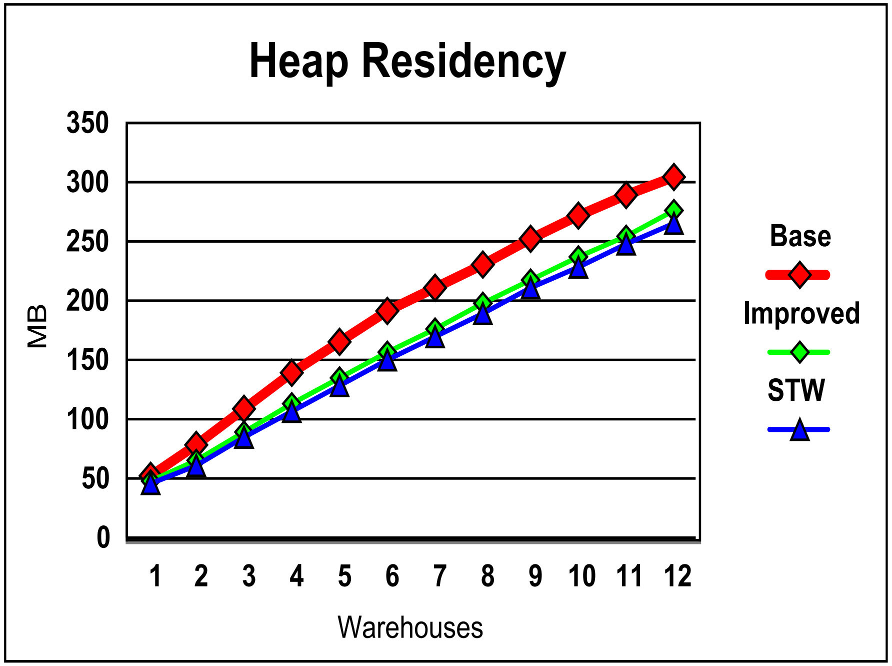
- SPECjbb. 6-way PPC. Heap size 448 MB
- 26.7% improvement (at tracing rate 1)

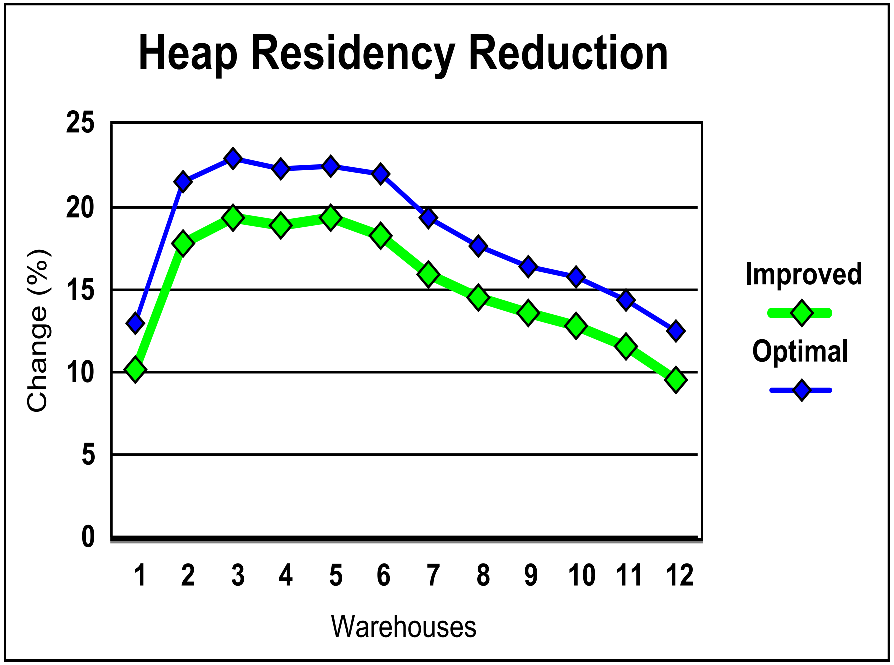




Results - Floating Garbage Reduction

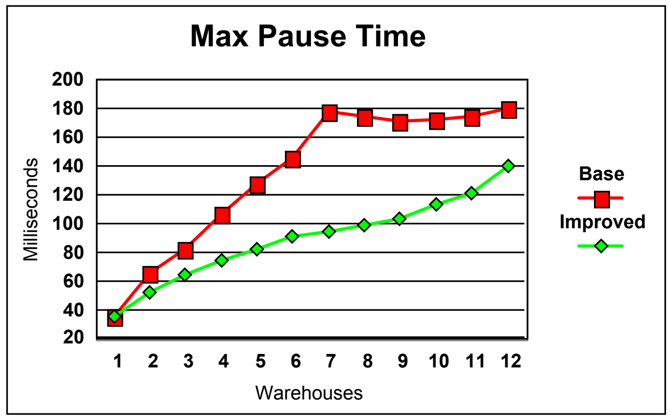
- SPECjbb. 6-way PPC. Heap size 448 MB
- 13.4% improvement in heap residency (at tracing rate 1)
- Almost all floating garbage eliminated

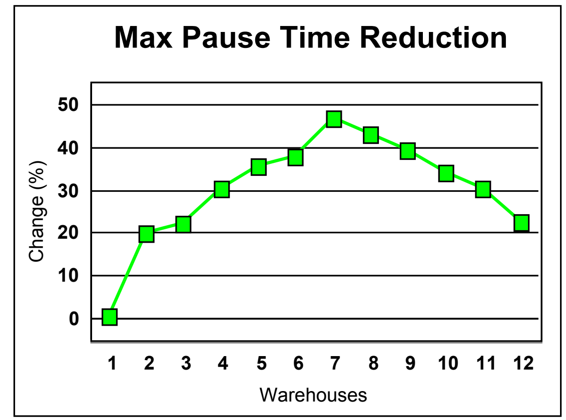


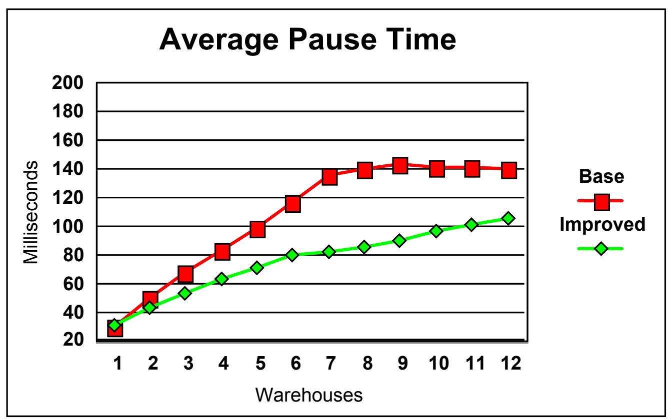


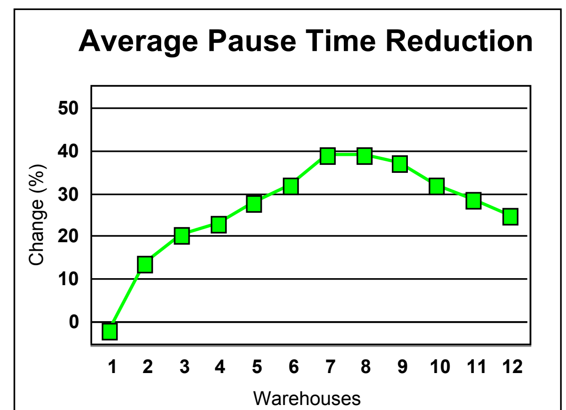
Results - Pause Time Reduction

- SPECjbb. 6-way PPC. Heap size 448 MB
- 33.3% improvement in average pause
- 36.4% improvement in max pause









Conclusions

- Two improvements on the popular mostly concurrent algorithm
  - Reduce repetitive work (don’t trace through dirty cards)
  - Reduces number of dirty cards (undirty cards with no traced objects)
- Substantial improvement
  - Improved benchmark throughput by 26%
  - Almost eliminated floating garbage (heap residency reduced by 13%)
  - Reduced average pause time by 33%

Reducing Pause Times for the Mostly Concurrent Collector

Endo-Taura 2002

Reducing Pause Times

- Pause time is determined by the final stop-the-world phase in which cards are finally cleaned while the program is halted.
- Manage work to achieve short-pauses:
  - Limit the number of dirty cards
  - If the halt become long, let the program threads resume.

Limit the number of dirty cards

- If the number of dirty cards exceeds a predetermined threshold, immediately scan one card.
- Advantage: limited number of cards will be scanned during the final phase.
- Disadvantage: a card may be rescanned repeatedly a large number of time.

Stop a Halt

- If a halt scans too many objects, then go back to concurrent mode.
- Advantage: Limited pause time.
- Disadvantage: threads may exhaust heap before collection ends.
    - Triggering becomes more complicated.

Conclusion

- Ideas may be used to reduce the pause times considerably.
- Throughput may be harmed.

Conclusion – Mostly Concurrent

- Most of the work done concurrently with program.
- Program is stopped for a short while in the end to clear (and scan) all dirty cards.
- Properties:
  - Short pauses, simple write-barrier
  - Overhead: write barrier, repeated scanning of dirty cards.
- One of the most popular commercially
  - Used (at least by) IBM, SUN, BEA.

Snapshot Copy-On-Write

Base: a snapshot collection

- A naïve collector:
  - Stop program threads
  - Create a snapshot (replica) of the heap
  - Program threads resume
  - Trace replica concurrently with program
  - Objects identified as unreachable in the replica may be collected in the real heap.

Problem: taking a replica of the heap is not realistic

A Virtual Replica

- A property of "typical" benchmarks:
  - A small part of the heap is being modified at any time interval.
- It is enough to copy only the part that is being modified. The rest can be read from the heap.
- Cannot tell in advance which areas will be modified by the program.
- Can copy each area before modified.

Using Page Protection

- To begin the collection, all mutators are stopped and all memory pages are write-protected.
- When mutators update an object, the interrupt on the protected page creates a copy of the page. Collector will use this copy for the trace.
- Copies may be "released" before sweep.
- Correctness: an unreachable object remains unreachable!
- Problem: traps are typically not efficient.

A Property of Some Operating Systems (e.g., UNIX Fork):

- Processes may request sharing memory pages.
- After the share, each process gets its own copy of the pages and any modifications done by one process are not visible to the other.
- A similar problem for operating system: should the memory be copied? If it is not modified, then it is not necessary.
- Some systems implement a “copy-on-write” strategy. Pages are shared until one of the processes modifies a page and then two copies are created.

GC with Copy-On-Write:

- To start GC: fork and share the heap.
- One process lets the program run.
- Second process traverses the heap to mark live objects.
- When marking done, second process hands the mark table to the first process, which runs the sweep.

Properties:

- 😌 No need for compiler support (write barrier).
- 😌 System implemented copy-on-write is efficient.
- 😌 Manual protection is usually inefficient.
  - Also, adding to page trap code…
- ☹️ System dependent.
- ☹️ Copy page is also triggered by non-pointer modifications.
- ☹️ Time for writing is unstable.
- ☹️ Overhead is not proportional: one integer modification causes a page copy.