Hierarchical Real Time Garbage Collection

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• Programming for RTJ is still made hard by memory management:
  • Java programmers are accustomed to garbage collection.
  • We would like to use real-time garbage collection (RTGC) - but sometimes performance is not good enough.
  • Programmers may be forced to use some form of manual memory management instead (scoped memory, object pools, eventrons, reflexes).
• RTGC introduction:
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  Interruptions from the collector are part of the real-time schedule.
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Following interruption, the time before the mutator gets to relinquish control from the collector should be small.
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For a given timeslice, the amount of time that the mutator is *guaranteed* to utilize, is maximized.
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• *RTGCs are not primarily designed to maximize overall application throughput!*

• All RTGCs “interfere” with the mutator by either actively interrupting it (Metronome) or requiring it to occasionally yield (Henriksson).
The problem with “normal” RTGCs.
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- The amount of interference from the RTGC is determined by the allocation rate of *all threads*, and the size of the whole heap.
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- The amount of interference from the RTGC is determined by the allocation rate of all threads, and the size of the whole heap.
- This leads to a kind of priority inversion: the heap usage of a non-real-time task may cause the GC to interfere with a real-time task.
• This problem affects all styles of RTGC (time-based, work-based, Henriksson-style).

• *It can be easily avoided if the part of the heap used by the real-time tasks is segregated from the part used by non-real-time tasks.*
Basic Strategy

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GC thread interferes with mutator
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- We segregate the heap into “heaplets”.
- Each heaplet gets its own collector thread.
- The collector for the non-real-time heaplets never interferes with real-time tasks.

Key
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We segregate the heap into “heaplets”.

Each heaplet gets its own collector thread.

The collector for the non-real-time heaplets never interferes with real-time tasks.

Thus - real-time code will not be affected by the footprint and allocation behavior of the non-real-time code.
What are heaplets?

- A “heaplet” is a user-specified heap partition, with a user-tuned RTGC thread.
- Any thread may use any heaplet for allocation at any time. The current allocation context is determined using an RTSJ-like API.
- Any thread may have references to objects in any heaplet.
- References between heaplets are allowed.
RTGC Example

Thread 1  Thread 2  Thread 3  GC Thread

Heap

Obj

Obj

Obj

Obj

Obj

Obj

Obj

Obj

Obj

Obj

Obj
RTGC with Heaplets Example

Heaplet 1

Heaplet 2
RTGC with Heaplets Example

Heaplet 1

Heaplet 2
RTGC with Heaplets Example

References between heaplets unrestricted
We introduce a heaplet hierarchy to increase the performance of cross-heaplet references.

A heaplet collector always scans child heaplets for references - thus, establishing new “up-hierarchy” references does not require barriers.

Others cross-heaplet references are handled using a barrier and global cross-reference list (“cross-set”).

Thus - establishing a cross-reference incurs a cost in both space and time.
Heaplet Hierarchy

Root Heaplet

Child Heaplet #1

Child Heaplet #2
Heaplet Hierarchy

“up-references” are guaranteed fast
Heaplet Hierarchy

“up-references” are guaranteed fast
“cross-references” are allowed, but come with a penalty
Putting it Together
Putting it Together

- Heap is manually partitioned into *heaplets*. 
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• Heap is manually partitioned into heaplets.

• Heaplets are manually arranged into a hierarchy, as a hint from the programmer about the likely directionality of references.
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- Heaplets are manually arranged into a *hierarchy*, as a hint from the programmer about the likely directionality of references.
- Each heaplet gets its own collector, user-tuned for the allocation and footprint behavior of the heaplet.
Putting it Together

- Heap is manually partitioned into heaplets.
- Heaplets are manually arranged into a hierarchy, as a hint from the programmer about the likely directionality of references.
- Each heaplet gets its own collector, user-tuned for the allocation and footprint behavior of the heaplet.
- Introducing heaplets into a correct program does not make it incorrect.
The HRTGC Algorithm

• Each heaplet gets a Metronome-style mark-sweep collector.

• Each collector is scheduled like the Metronome - but with control of schedules extended to include phasing.

• Cycles of cross-heaplet references are handled using a global cycle collector. Because garbage cycles are rare, the cycle collector runs at a very low rate - in fact it runs at a zero rate in our benchmarks.
Implementation and Evaluation
• We use the OpenVM RTJVM and J2c ahead-of-time compiler on the Linux operating system.

• HRTGC is implemented as a memory management configuration in the OVM.

• OVM already implements a Metronome-like RTGC, which we use as a baseline.
Two real-time Java benchmarks were used for comparing regular RTGC and HRTGC:

- RTZen, a 202 KLoC CORBA implementation from UC Irvine, and
- CD, a 41 KLoC benchmark developed at Purdue.

Both benchmarks were originally written to use RTSJ scoped memory. We have previously converted both to use our Metronome-like RTGC.

For this evaluation, we again converted the benchmarks, this time to use heaplets.
Conversion to use HRTGC

- Converting CD:
  - The CD use a producer-consumer pattern. We placed the producer and consumer in separate heaplets.

- Converting RTZen:
  - We place the core of Zen into its own heaplet.
  - The only changes were instrumentation in the main() method to create the ORB in our new heaplet.
  - Thus, the Zen benchmark demonstrates not only the performance benefits of HRTGC, but the ease with which code can be refactored to use it effectively.

- Both benchmarks use 227_mtrt from SPECjvm98 as a noise maker.
Measurements

- We use a fixed total footprint for all configurations.
- The collector schedules are optimized for highest utilization while not allowing the memory usage to diverge.
- Both CD and RTZen are event-driven - thus, we record the total time required to handle each event - a quantity we call the *response time*.
- Additionally, we measure the *minimum mutator utilization* (MMU).
RTZen Response Time
RTZen with RTGC

Response time in microseconds

Number of Iterations

Minimum Mutator Utilization
RTZen with RTGC

Worst case: 952us
RTZen with HRTGC
RTZen with HRTGC

HRTGC Worst case: 811 us
RTZen with HRTGC

RTGC Worst case: 952μs

HRTGC Worst case: 811μs
RTZen with HRTGC

Response time in microseconds

RTGC Worst case: 952us
HRTGC: 15% better
HRTGC Worst case: 811us
CD Response Time
Utilization

The figure shows response time in microseconds for different collectors and cases. The response time for the collector cases is observed to be around 5000-6000 microseconds, indicating a high utilization rate.

The TGC4 response time in microseconds is represented in the graph. The y-axis is labeled as "Response time in microseconds" and the x-axis as "Number of Iterations".

In the worst-case scenario, HR TGC uses a total of...
Utilization

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CD with HRTGC

Response time in microseconds

Number of Iterations
CD with HRTGC

HRTGC Worst case: 6.113ms
CD with HRTGC

RTGC Worst case: 8.255ms

HRTGC Worst case: 6.113ms
CD with HRTGC

RTGC Worst case: 8.255ms

HRTGC: 26% better

HRTGC Worst case: 6.113ms
• Minimum mutator utilization (MMU) shows the worst-case amount of time the mutator would get for a timeslice of a given length.

• Thus - MMU shows utilization (a number from 0 to 1, where 1 is better) versus timeslice size (in this case, in nanoseconds).

• We display MMU that has been empirically measured for our two benchmarks (RTZen and CD).
RTZen MMU

![Graph showing Mutator Utilization vs. Window size in nanoseconds for different systems: HRTGC Zen, RTGC, HRTGC 227_mtrt + Zen.](image-url)
Utilization

Case

Corresponding

The collector

Leading

Notebook.nb

The corresponding collector leading is increasingly observed for response time in microseconds. The utilization of the collector is shown in the graph.

The graph shows the utilization of HRTGC and RTGC. The utilization is plotted against the window size in nanoseconds. HRTGC has a higher utilization compared to RTGC, especially for window sizes greater than $10^7$ nanoseconds.
A more in-depth discussion of the algorithm, and the results, is found in the paper.
Questions/Comments