GC Optimizations You Never Knew Existed

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IBM

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Outline

1. Introduction
2. Garbage Collection Algorithms
3. Dynamic Breadth First Scan Ordering
4. Double Map Arraylets
5. Off-heap Management
6. Summary
A Little bit About Igor

1. Software Developer at IBM
2. Masters University of Waterloo
3. Interested in Systems, Compilers, ML/AI
4. Tennis Addict
A Little bit About Jon

1. VM/GC Developer at IBM
2. Studied Systems Engineering at Carleton University
3. Most Interested in ML/AI, Blockchain Technology, and of course, GC
4. Fun Fact: 2nd youngest of 11 children
Latest release

1. Choose a Version
   - OpenJDK 8 (LTS)
   - OpenJDK 9
   - OpenJDK 10
   - OpenJDK 11 (LTS)
   - OpenJDK 12
   - OpenJDK 13 (Latest)

2. Choose a JVM
   - HotSpot
   - OpenJ9

The place to get OpenJDK builds
For both

OpenJDK + OpenJ9
or
OpenJDK + Hotspot

https://adoptopenjdk.net
Eclipse OpenJ9
Created Sept 2017

http://www.eclipse.org/openj9
https://github.com/eclipse/openj9

Dual License:
Eclipse Public License v2.0
Apache 2.0

Users and contributors very welcome
https://github.com/eclipse/openj9/blob/master/CONTRIBUTING.md
Garbage Collection
Garbage Collection

“Garbage Collection (GC) is a form of automatic memory management. The garbage collector attempts to reclaim memory occupied by objects that are no longer in use by the application.”
Garbage Collection

I. Allocation of memory
II. Identification of live data
III. Reclamation of garbage
Garbage Collection

Positives
- Automatic memory management
- Help reduce certain categories of bugs

Negatives
- Require additional resources
- Causes unpredictable pauses
- May introduce runtime costs
- Application has little control of when memory is reclaimed
GC Algorithms [1]

- Region based
- Mark Sweep
- Mark Sweep Compact
- Generational
- Parallel
- Concurrent
- Reference counting
Garbage Collection Policies

-Xgcpolicy:

gencon CS – pauseless collector

balanced – region based collector
-Xgcpolicy:gencon

Generational copy collector

Provides a significant reduction in GC STW pause times

Introduces write barrier for the remembered set

Concurrent global marking phase
-Xgcpolicy:gencon Heap

Heap is divided into Nursery and Tenure Spaces

Nursery  Tenure
-Xgcpolicy:gencon heap

Heap is divided into Nursery and Tenure Spaces

The Nursery is divided into 2 logical spaces: Allocate and Survivor

Allocate | Survivor | Tenure

Heap
-Xgcpolicy:gencon GC

Scavenge 1

Scavenge 2

Global Start

Scavenge 3

Global End
-Xgcpolicy:gencon GC

Write Barrier

Why do we need a write barrier?
-Xgcpolicy:gencon GC

Write Barrier

Why do we need a write barrier?

The GC needs to be able to find objects in the nursery which are only referenced from tenure space
How's the write barrier implemented?

```java
private void setField(Object A, Object C) {
    A.field1 = C;
}
```
private void setField(Object A, Object C) {
    A.field1 = C;
    if (A is tenured) {
        if (C is NOT tenured) {
            remember(A);
        }
    }
}
private void setField(Object A, Object C) {
  A.field1 = C;
  if (A is tenured) {
    if (C is NOT tenured) {
      remember(A);  // ←
    }
    if (concurrentGCActive) {
      cardTable->dirtyCard(A);
    }
  }
}
-Xgcpolicy:gencon GC
Concurrent Scavenger

Generational copy collector

Introduces read Barrier for Concurrent Compact

Pauseless GC
-Xgcpolicy:gencon GC
Concurrent Scavenger

Heap is divided into Nursery and Tenure Spaces

The Nursery is divided into 2 logical spaces: Allocate and Survivor

Allocate | Survivor | Tenure
----------|----------|--------

Heap
-Xgcpolicy:gencon GC
Concurrent Scavenger
Concurrent Scavenger

Multiple GC threads trying to move objects

And mutator threads trying to access these same objects
Concurrent Scavanger

From Space (Allocate/Evacuate)
- Class
  - Field1
  - Field2

To Space (Survivor)
- Class
  - Field1
  - Field2

GC Thread1
Mutator Thread2
Concurrent Scavanger

From Space
(Allocate/Evacuate)

Forward Pointer

Field1

Field2

To Space
(Survivor)

Class

Field1

Field2

Class

Field1

Field2
Concurrent Scavanger

From Space (Allocate/Evacuate)

Forward Pointer
Field1
Field2

To Space (Survivor)

Class
Field1
Field2

Class
Field1
Field2

GC Thread1
Mutator Thread2
Dynamic Breadth First Scan Ordering

Key Concepts

• Example 1 – Gencon with Breadth First Scan Ordering

• Example 2 – Gencon with Dynamic Breadth First Scan Ordering

Results & Takeaways
Locality

- 90/10 rule
- Caching
- Cache Prefetching
- Caching Hit to Miss ratio
Hot Fields and Access Patterns

• According to the 90/10 rule – if 90% of time is spent in 10% of code, there is likely some very hot object access patterns and very hot fields
• A hot field is a field that is frequently accessed by an object instance
• A hot access pattern is an object access pattern or path that occurs frequently
Hot Fields and Access Patterns - Example

- A
  - B: 10%
  - C: 90%
    - D: 10%
    - E: 90%
    - F: 10%
    - G: 90%

- 90%
- 10%
Hot Fields and Access Patterns - Example

Ideally, we would have A, C and G spatially localized in memory, and B and E spatially localized in memory.
Ex: Breadth First Gencon GC

Initial

Allocate

Survivor

Tenure

Root Set

A F
Ex: Breadth First Gencon GC

Initial

Allocate

Survivor

Tenure

Final

Allocate

Survivor

Tenure

Root Set

A

F
With common access patterns of A→ C→ G and B→ E, the existing breadth first scan ordering implementation is clearly not optimal with regards to locality.
Goal of Dynamic Breadth First Scan Ordering

- Optimize breadth first scan ordering for improved locality
- Leverage available JIT information for improved locality
- Render locality dependent optimization mechanisms more effective
Relevant Existing Infrastructure

• What is a compiler?
• What is an optimizing compiler?
• What is dynamic compilation?
What is a Compiler?

• A translator
  – Takes code written in one (source) language and produces equivalent code in another (target) language

• Possible source and target languages:
  – Source code to machine code (gcc, clang, etc.)
  – Source code to bytecode (javac)
  – Bytecode to machine code (Testarossa JIT)
  – ... and more
What is an Optimizing Compiler?

- Tries to produce “good” code
- Good (optimized) code should:
  - Execute faster
  - Require less memory
  - Consume less power
What is dynamic compilation?

- Interpreter invokes the compiler *just in time* before a method becomes a performance problem
- The Just-In-Time compiler (*jit*) turns bytecode into much faster native code
- Eclipse OpenJ9’s Testarossa JIT compiler is an *optimizing compiler*
Relevant JIT Compiler Information Leveraged

- Applications consists of compilation instances (logical compilation entities – i.e. methods)
- The JIT Compiler is a tiered compilation compiler
- IBM Testarossa compilation levels - cold, warm, hot, very hot, scorching
- Each compilation is divided into “blocks” where the relative hotness of each code block within the compilation gets a normalized block “hotness” value from 1-10000
Relevant JIT Compiler Information Leveraged

• When a field is accessed within a compilation, we can compute an overall “hotness” value approximation for the field access using:
  • the compilation optimization level of the method
  • the block “hotness” of the block within the compilation where the field was accessed
• This “hotness” value is computed for every field access of every compilation
• For each field of a class, we can aggregate these “hotness” values for all field access’ across all method compilations
Relevant JIT Compiler Information Leveraged

• Hotness values are aggregated via a hotness aggregation algorithm
• Recursively depth copy the object’s two hottest fields directly after an object is copied if hot fields for the object exist
• Assure minimum hotness requirements are met before allowing a field to be depth copied
# Simple Field Hotness Calculation Example

<table>
<thead>
<tr>
<th>Method</th>
<th>Compilation Level</th>
<th>Compilation Level Weighting</th>
<th>Block Hotness Within Compilation Where Field is Accessed</th>
<th>Hotness Contribution</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Hot</td>
<td>10</td>
<td>50</td>
<td>500</td>
</tr>
<tr>
<td>B</td>
<td>Scorching</td>
<td>100</td>
<td>40</td>
<td>4000</td>
</tr>
<tr>
<td>C</td>
<td>Warm</td>
<td>1</td>
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**Current Total Field Hotness**: 5500
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Ex: Dynamic Breadth First Gencon GC

Root Set
A
F

Allocate
A
B
C
D
E
F
G

Survivor
H

Tenure

A

B

C

D

E

F

G

10%
90%
10%
90%
10%
90%

90%
10%
Ex: Dynamic Breadth First Gencon GC
Ex: Dynamic Breadth First Gencon GC
Ex: Dynamic Breadth First Gencon GC

Root Set

Allocate

Survivor

Tenure

Scan cache

Copy cache

D

E

F

G

B

C

A

H

Ex: Dynamic Breadth First Gencon GC

Root Set

Allocate

Survivor

Tenure

Scan cache

Copy cache

D

E

F

G

B

C

A

H

Ex: Dynamic Breadth First Gencon GC

Root Set

Allocate

Survivor

Tenure

Scan cache

Copy cache

D

E

F

G

B

C

A

H

Ex: Dynamic Breadth First Gencon GC

Root Set

Allocate

Survivor

Tenure

Scan cache

Copy cache

D

E

F

G

B

C

A

H

Ex: Dynamic Breadth First Gencon GC

Root Set

Allocate

Survivor

Tenure

Scan cache

Copy cache

D

E

F

G

B

C

A

H

Ex: Dynamic Breadth First Gencon GC

Root Set

Allocate

Survivor

Tenure

Scan cache

Copy cache

D

E

F

G

B

C

A

H

Ex: Dynamic Breadth First Gencon GC

Root Set

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Survivor

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G

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Survivor

Tenure

Scan cache

Copy cache

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E

F

G

B

C

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Ex: Dynamic Breadth First Gencon GC

Root Set

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Scan cache

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G

B

C

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H

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Root Set

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F

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Tenure

Scan cache

Copy cache

D

E

F

G

B

C

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Scan cache

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D

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Ex: Dynamic Breadth First Gencon GC

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Survivor

Tenure

Scan cache

Copy cache
Ex: Dynamic Breadth First Gencon GC

Root Set

Scan cache

Copy cache

Allocate

Survivor

Tenure
Gencon GC – Ex: **Dynamic** Breadth First

**Root Set**

- A
- F

**Scan cache**

**Copy cache**

- A
- C
- G
- F

**Allocate**

- B
- D
- E

**Survivor**

- A
- C
- G
- F

**Tenure**

- H
Gencon GC – Ex: **Dynamic Breadth First**

**Work list**

A | C | G | F

**Scan cache**

**Copy cache**

**Allocate**

B | D | E | A | C | G | F | H

**Survivor**

**Tenure**
Gencon GC – Ex: Dynamic Breadth First

Work list

Scan cache

Copy cache

Allocate

Survivor

Tenure
Gencon GC – Ex: Dynamic Breadth First

Work list

Q¹ R¹ L¹

Scan cache

A C G F B

Copy cache

A C G F B

Allocate

D E A C G F B

Survivor

H

Tenure
Gencon GC – Ex: **Dynamic** Breadth First

**Work list**

Q¹ R¹ L¹

**Scan cache**

A C G F B E

**Copy cache**

A C G F B E

**Allocate**

D A C G F B E

**Survivor**

H

**Tenure**
Gencon GC – Ex: Dynamic Breadth First

Work list

Scan cache

Copy cache

Allocate

Survivor

Tenure
Gencon GC – Ex: **Dynamic** Breadth First

**Work list**

\[ \text{Q}^1, \text{R}^1, \text{L}^1 \]

**Scan cache**

\[ \text{A} \rightarrow \text{C} \rightarrow \text{G} \rightarrow \text{F} \rightarrow \text{B} \rightarrow \text{E} \]

**Copy cache**

\[ \text{A} \rightarrow \text{C} \rightarrow \text{G} \rightarrow \text{F} \rightarrow \text{B} \rightarrow \text{E} \]

**Allocate**

\[ D \rightarrow A \rightarrow C \rightarrow G \rightarrow F \rightarrow B \rightarrow E \]

**Survivor**

\[ \text{H} \]

**Tenure**
Gencon GC – Ex: Dynamic Breadth First

Work list

Scan cache

Copy cache

Allocate

Survivor

Tenure
Gencon GC – Ex: Dynamic Breadth First

Work list

Q¹ R¹ L¹

Scan cache

A C G F B E D

Copy cache

A C G F B E D

Allocate

Survivor

Tenure
Gencon GC – Ex: Dynamic Breadth First

Work list

Scan cache

Copy cache

Allocate

Survivor

Tenure
Gencon GC – Ex: **Dynamic Breadth First**

**Work list**

**Scan cache**

**Copy cache**

**Allocate**

**Survivor**

**Tenure**
Gencon GC – Ex: Dynamic Breadth First

Initial

Allocate

Final

Allocate

Survivor

Tenure

Survivor

Allocate

Tenure
Breadth First vs. Dynamic Breadth First

Breadth First

<table>
<thead>
<tr>
<th>A1</th>
<th>F1</th>
<th>B1</th>
<th>C1</th>
<th>D1</th>
<th>E1</th>
<th>G1</th>
<th>H</th>
</tr>
</thead>
<tbody>
<tr>
<td>10%</td>
<td>90%</td>
<td>10%</td>
<td>90%</td>
<td>10%</td>
<td>90%</td>
<td>10%</td>
<td></td>
</tr>
</tbody>
</table>

Dynamic Breadth First

<table>
<thead>
<tr>
<th>A1</th>
<th>C1</th>
<th>G1</th>
<th>F1</th>
<th>B1</th>
<th>E1</th>
<th>D1</th>
<th>H</th>
</tr>
</thead>
<tbody>
<tr>
<td>79%</td>
<td></td>
<td></td>
<td></td>
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</tbody>
</table>
Example Takeaways

• Dynamic Breadth First Scan Ordering enables the possibility to have objects accessed frequently spatially localized in memory
• Among other things, Dynamic Breadth First Scan Ordering will likely result in a higher cache hit ratio compared to standard Breadth First Scan Ordering
Results – Breadth First vs Dynamic Breadth First

• 2-8% throughput improvements on various benchmarks
• Negligible difference in application compile time
• 2-3% increase in average application GC pause time
• Future development iterations will be optimized to reduce GC overhead while continuing to improve application throughput efficiency
Dynamic Breadth First Summary

• Leverage existing JIT infrastructure

• Every method is divided into logical blocks where blocks are assigned a normalized hotness value between 1 – 10000

• The overall “hotness” of each field access depends on 2 key factors:
  • The block frequency of the compilation block the field has been reported in
  • The tiered compilation level that the compiler is currently compiling the method at when the field has been reported
-Xgcpolicy:balanced

Region based generational collector

Provides a significant reduction in max GC STW pause times

Introduces a write barrier to track inter region references

Incremental heap defragmentation
-Xgcpolicy:balanced Heap

Heap is divided into a fixed number of regions

- Region size is always a power of 2
- Attempts to have between 1000-2000 regions
- Bigger heap == bigger region size
-Xgcpolicy:balanced Heap

Allocate from Eden regions

- Eden can be any set of completely free regions
- Attempts to pick regions from each NUMA node
-Xgcpolicy:balanced Heap

No non-array object can be larger than a region size

- If \( \text{object\_size} > \text{Region\_size} \) throw OutOfMemoryError

Large arrays are allocated as **arraylets**

- Arrays less than region size are allocated as normal arrays
-Xgcpolicy:balanced GC

PGC 1  GMP start  PGC 2  GMP End  PGC 3

GMP cycle
-Xgcpolicy:balanced Global Mark Phase (GMP)

- Does not reclaim any memory
- Performs a marking phase only
- Scheduled to run in between PGCs
- Builds an accurate mark map of the whole heap
- Mark map is used to predict region ROI for PGC
-Xgcpolicy:balanced
-XgcPolicy:balanced

Write Barrier

Why do we need a write barrier?

Balanced PGCs can select any region to be included in the collect phase

Similar to the generational barrier, the GC needs to know which regions reference a given region
-Xgcpolicy:balanced
Write Barrier

How is the write barrier implemented?

```java
private void setField(Object A, Object C) {
        A.field1 = C;
}
```
-Xgcpolicy:balanced

Write Barrier

```java
private void setField(Object A, Object C) {
    A.field1 = C;
    dirtyCard(A);
}
private void checkCards() { // Beginning of PGC
    for (eachCard)...
        if (findRegion(A) != findRegion(C)) {
            addRSCLEntryFor(C, A);
        }
}
```
Arraylets

Large Arrays that cannot fit into a single region

- Array is created from construct comprising of an arraylet spine and 1 or more arraylet leaves
- An arraylet spine is allocated like a normal object
- Each leaf consumes an entire region
Arraylets

Heap

Arraylet leaves

Arraylet Spine

Header

Data references
Arraylets

Arraylets were introduced so that arrays were more cleverly stored in the heap for balanced and metronome GC policies.

Some APIs require a contiguous view of an array
Arraylets

Some APIs require a contiguous view of an array

The case of Java Native Interface (JNI) Critical APIs

JNI Critical is used when the programmer wants direct addressability of the object.
Arraylets
Arraylets
Arraylets

Very expensive!!
Arraylets
Double Mapping

Make large arrays (discontiguous arraylets) look contiguous

Physical memory is limited

Virtual Memory address space is large in 64 bit systems, $2^{64}$ in fact compared to 32 bits in 32 bit systems
Arraylets
Double Mapping

Map 2 virtual memory addresses to the same physical memory address

Any modifications to the newly mapped address will reflect the original array data, and vice-versa
Arraylets
Double Mapping

Comparing JNI critical operations, array operations received **30x boost** in speedup
Can We do better?

Double Mapping Arraylets are only available on newer version of Linux

Off-heap management for large objects
Double Mapping Drawbacks

Doable with `shm_open(3)` but:
- It returns a file descriptor (backed by shared memory)
- Linux systems have cap on max `shm_open` shared memory

Doable with `memfd_create(2)` but:
- It also returns a file descriptor
- Behaves like regular file backed by RAM
- Only available on newer GLIBC versions
Off-heap Management for Large Objects

- Does not require file descriptors
- It also takes advantage of vast virtual memory space
- Will only be available in 64bit systems
Off-heap Management
Off-heap Management

In-Heap

$X =$ heap size

$n$ regions

Off-Heap

$X_0$ $X_1$ $X_2$ $X_3$ $X_{n-1}$

Proxy Object

Container elements also points to associated proxy object

Previously committed and recently decommitted. (Candidate for next large object allocation)
Off-heap Management

What's the smallest off-heap that we can come up with so that we'll never have to compact it?
Off-heap Management

The smallest object that we'll be storing at off-heap is as big as 2 regions

If we're greedy

\[
\text{off_heap_size} = \text{in_heap_size} \times \text{region_count}
\]

\[
\text{off_heap_size} = 2\text{TB} \times 1024 \; // \; == \; 2\text{PB} \; == \; 2^{51}\text{B}
\]
Off-heap Management

What's the worst possible allocation pattern we can get?

1. Allocate objects of region size 2
2. Free half of objects with a pattern of every other object
3. Allocate objects of region size 3
Off-heap Management

What's the worst possible allocation pattern we can get?

Free half of objects with a pattern of every other object

Allocate objects of region size 7

Free half of objects with a pattern of every other object
Off-heap Management

There's a pattern!
Now we can calculate off-heap size with a better upper bound
Off-heap Management

If we're smart

\[
\text{off_heap_size} = \text{ceil}(\log_2(\text{region_count}) \times \text{in_heap_size} / 2)
\]

\[
\text{off_heap_size} = \text{ceil}(\log_2(1024) \times 2\text{TB} / 2) \quad // \quad == \quad 20\text{TB} \sim 2^{44} \text{ B}
\]

Before

\[
\text{off_heap_size} = 2\text{TB} \times 1024 \quad // \quad == \quad 2\text{PB} \quad == \quad 2^{51} \text{ B}
\]
Off-heap Management

Positives

• Any platform that supports virtual memory can benefit
• Unburdens in-heap from large object allocation
• Off-heap will never need to be compacted
• Does not require file descriptors

Negatives

• Whenever we commit memory at off-heap we must decommit memory at in-heap, and vice-versa
• One extra level of indirection to access array data
GC Policies

- **Gencon**
  - Old/new space | generational | copy collector

- **Balanced**
  - Region based | generational | copy collector

- **Metronome**
  - Region based

- **Gencon CS**
  - Read barrier

- **Common GCs**
  - Throughput centric

- **CMS**

- **G1 GC**

- **ZGC**

- **Shenandoah**

- **Azul C4**
  - Pauseless GC with special hardware

- **Pauseless GCs**
Summary

throughput = \frac{\text{GC Pause}}{x}

Perfect STW GC vs Perfect Pauseless GC

- Higher Throughput
- Longer pauses

- Lower Throughput
- Shorter pauses

Dynamic Breadth First Scan Ordering

Double Mapping

Off-heap Object Management
Questions?
References