Explorations of the Three Legged Performance Stool

Charlie Hunt
JVM & Performance Junkie

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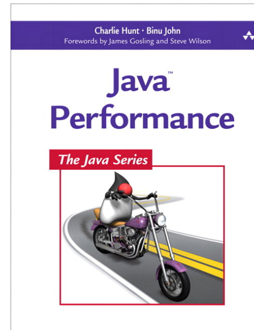
Who is this guy?

Charlie Hunt

- Currently leading a several HotSpot JVM projects at Oracle
- Held various performance architect roles at Oracle, Salesforce.com & Sun Microsystems
- Lead author of ***Java Performance***, published Sept 2011



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Who is this guy?

And for those who enjoy reading in additional languages …

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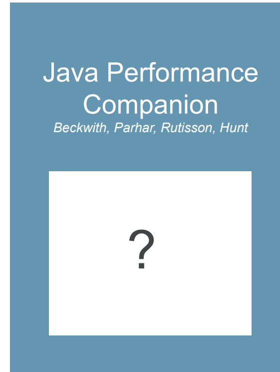
Who is this guy?

And coming soon to a book store near you …

Java Performance Companion – book cover in process

Authors: Monica Beckwith, Bengt Rutisson, Poonam Parhar & Charlie Hunt



Intended to compliment the material found ***Java Performance***

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What to expect

This session is about understanding the relationship between throughput, latency and footprint along with, understanding where system capacity fits in.

And, reasoning about the benefit & impact of each when making changes, JVM configuration or application.

We will also look at a case study / example.

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Agenda

- The key performance attributes
- (Very) quick re-visit of the HotSpot JVM GCs
- Reason about trade-offs with the performance Attributes
- Case Study (a JDK 9 feature)

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The Performance Attributes

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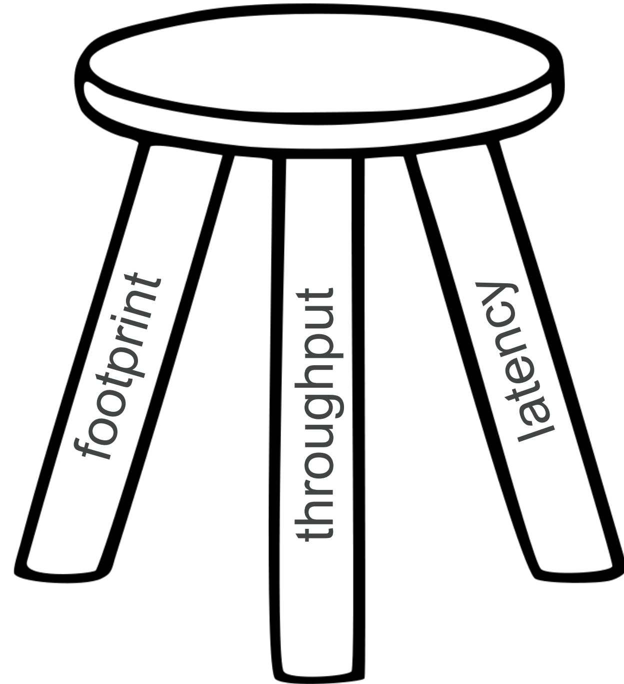
Three Legged Stool

- Throughput
- Latency
- (Memory) Footprint



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2 of 3 Principle

Improving one or two of these performance attributes, (throughput, latency or footprint) results in sacrificing some performance in the other.

Hunt, John. Java Performance. Upper Saddle River, NJ, Addison-Wesley, 2011

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2 of 3 Principle (updated)

Improving all three performance attributes [usually] requires a lot of non-trivial [development] work.

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Another Principle - (yet to be named)

An improvement in throughput and/or latency may reduce or lower the amount of available CPU to the application, or other applications executing on the same system. Thus impacting the capacity of the system.

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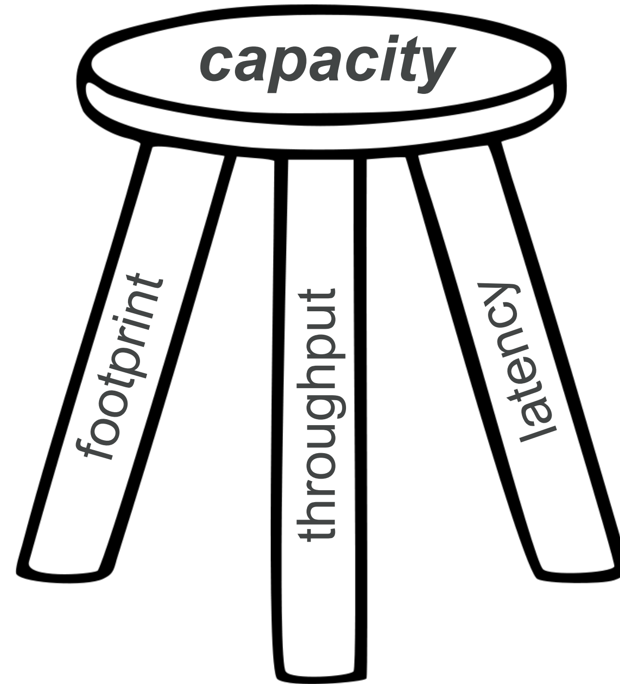
Perhaps an Enhanced Three Legged Stool ?

- Throughput
- Latency
- (Memory) Footprint
- ***Capacity***



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Quick (re)visit of HotSpot JVM GCs

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Generational GCs

- [Almost] all modern JVMs use a generational GC
  - Segregate objects by age into different spaces, and bias collection of younger objects
  - Typically two generations; young & old
- JVMs with generational GCs
  - HotSpot – all GCs supported by Oracle
  - Zing – C4 GC
  - J9 – all AFAIK … admit I'm not familiar with J9's GCs

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Why Generational GC ?

- Weak generational hypothesis
  - Most objects die young
- Generally accepted reason for generational GCs
  - Improved throughput, and scaling to large Java heaps

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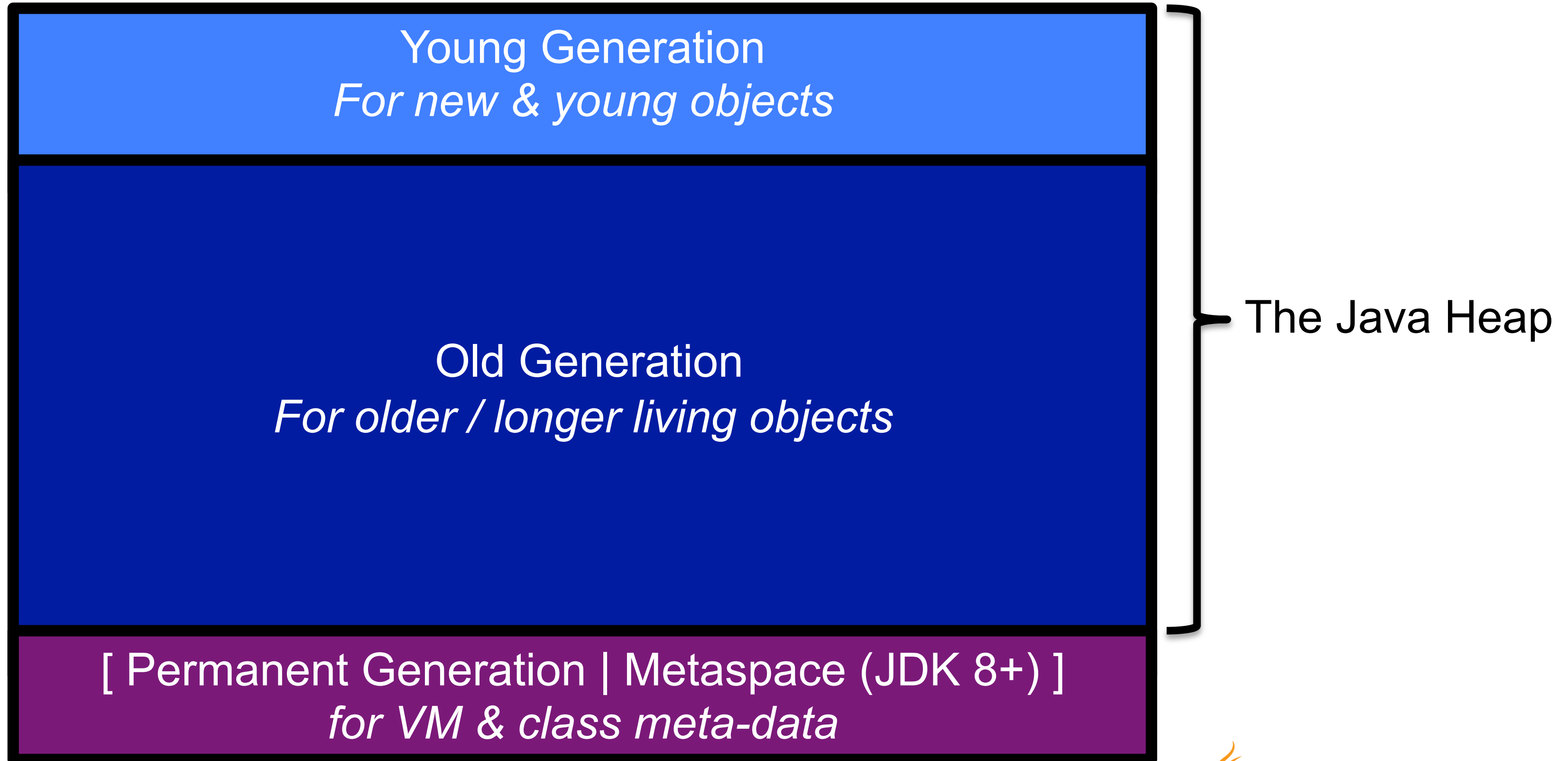
HotSpot JVM Java Heap Layout



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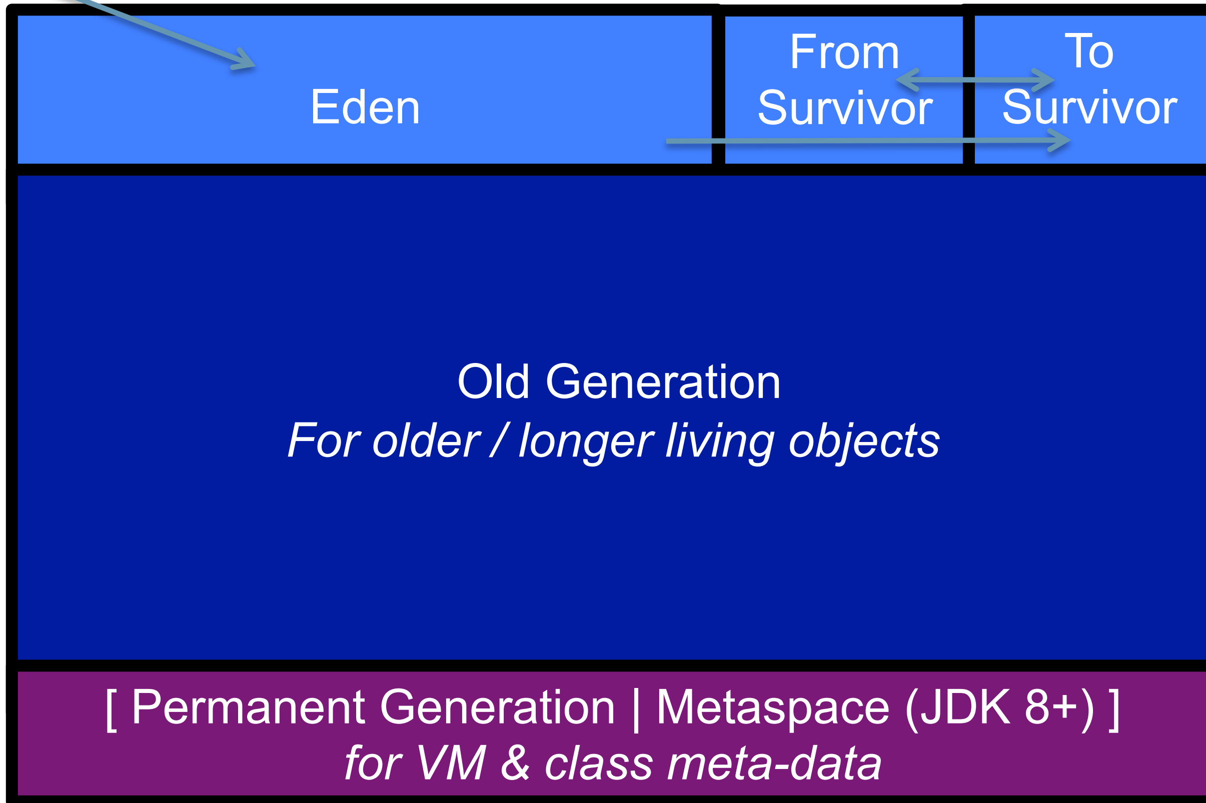
HotSpot JVM Java Heap Layout



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Things to reason about wrt GC & your application

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GC Duration (pause time)

What impacts pause time duration?

- Duration of GC activity is mostly a function of the number of live objects
  - Other factors
    - Object graph structure
    - Use of, and number of Reference objects
    - Memory locality

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GC Duration (pause time)

Strategies to reduce (young) GC duration

- Reduce young generation Eden size
  - Smaller space implies fewer live objects (may not always be true!)

Eden (1 GB)

- Concurrent young collector?
  - Eliminate pause by collecting concurrently

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GC Duration (pause time)

Consequences

- Reduce young generation Eden size
  - Likely lower throughput due to more frequent application pauses
  - More frequent GCs due to smaller size (more on that in a moment)
  - More object promotions to old generation due more rapid object aging
- Concurrent young collector
  - Available capacity impact due to higher CPU utilization from concurrent collection activity
  - Throughput and/or latency may be impacted due to CPU usage and CPU cache eviction
  - Footprint may be impacted due to floating garbage

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GC Duration (pause time)

Other alternatives

- Lower application's object allocation rate
  - Lower injection rate or load on the application
    - Lower system throughput, & lower system capacity, maybe better latency
  - Capture memory profiles and reduce object allocations
    - Requires (development) work, and may be non-trivial
    - Might actually increase number of live objects at each young GC
      - Implies a potential increase in pause time
    - Throughput and latency may (or should) improve due to less frequent GC events

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Young GC Frequency

Often not thought of … and applicable to concurrent collection too

- How often Young GC's occur influenced by
  - Application object allocation rate – how fast it's allocating objects
  - Size of Eden space
    - This applies to the HotSpot JVM
    - For other generational JVMs it will be the size of the space where new objects are allocated
    - For STW collectors, once that space is exhausted, a GC event occurs
    - For concurrent collectors, there's usually an occupancy threshold that once it's surpassed, a concurrent GC event commences

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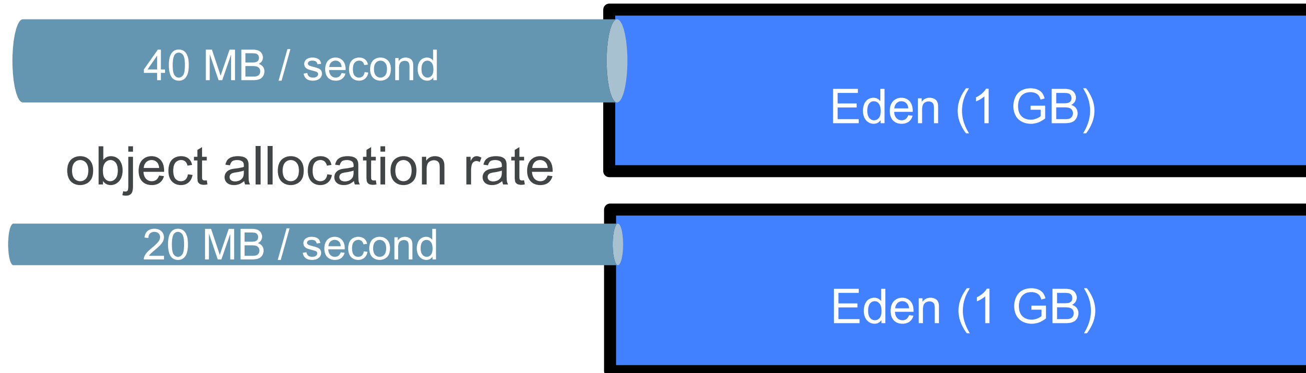
Influencing Minor GC Frequency

Reduce object allocation rate

- Eden space fills more slowly with reduced object allocation rate



- Obvious, right? 2x drop in allocation rate, time to fill Eden space increases 2x, i.e. minor GC frequency cut in ½

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Influencing Minor GC Frequency

Make Eden size bigger (assuming same object allocation rate)

- Same allocation rate, 2x increase in Eden space, time between GC increases 2x, i.e. minor GC frequency cut in ½

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Young GC Frequency

Consequences

- Reduce object allocation rate (saw this before, right?)
  - Lower injection rate or load on the application
    - Lower system throughput, lower system capacity, maybe better latency
  - Capture memory profiles and reduce object allocations
    - Requires (development) work, and may be non-trivial
    - Might actually increase number of live objects
      - Implies a potential increase in pause time, or GC time
    - Throughput and latency may (or should) improve

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Young GC Frequency

Consequences

- Increase young generation Eden size
  - Less frequent GCs due to larger size
  - Fewer object promotions due more effective object aging
  - Likely higher throughput due to less frequent application pauses or collection activity
    - All 3 probably sound attractive
  - Worse case latency may be higher due to larger space to GC
    - GC duration / pause time could be longer
    - Hmmm … may be not so attractive?

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Young GC Frequency

Consequences

- What about the potential impact with a concurrent young generation collector ?
  - Less impact on available capacity due to less frequent collection activity
  - May see higher throughput and/or lower latency due to lower CPU usage and lower CPU cache eviction due to less frequent concurrent collection activity
  - Larger footprint due to larger young generation size

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Old GC Duration

What influences Old GC duration?

- Number of live objects and objects to move for compaction
  - Other factors
    - Object graph structure
    - Use of, and number of Reference objects
    - Memory locality
- Differing GC algorithms; stop the world, mostly concurrent, concurrent, mark sweep, mark sweep compact, etc.
  - And, details within the GC algorithm, i.e. mostly concurrent write-barrier implementation, concurrent read & write barrier implementations

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Old GC Duration

Strategies to reduce (old) GC duration (pause time)

- Reduce old generation size
  - Smaller space implies fewer live objects (may not always be true!)

Old (2 GB)

- Use a concurrent, or mostly concurrent old collector?
  - Eliminate, or reduce lengthy pause(s) by collecting concurrently or mostly concurrently

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Old GC Duration (pause time)

Consequences

- Reduce old generation size
  - More frequent GCs due to smaller size, i.e. space fills faster
  - Throughput and/or latency may be impacted due to collections occurring more frequently
  - Available capacity impact due to higher CPU utilization from more frequent collection activity
  - Likely a smaller footprint due to smaller old generation size

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Old GC Duration (pause time)

Consequences of reduced old gen size

- What about using a concurrent, or mostly concurrent old collector
  - Available capacity impact due to higher CPU utilization from concurrent collection activity
  - Throughput and/or latency may be impacted due to CPU cache eviction from concurrent GC activity
  - Footprint may be impacted due to floating garbage

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Old GC Frequency

Applicable to mostly concurrent collectors too

- How often Old GC's occur influenced by
  - Object promotion rate – how many objects promoted from young to old
  - Size of the Old space
    - This applies to the HotSpot JVM
    - For other generational JVMs it will be the size of the space where older objects are promoted / allocated
- For STW collectors, once the space is exhausted, a GC event occurs
- For (mostly) concurrent collectors, there's usually an occupancy threshold that once it's surpassed, a concurrent GC event commences

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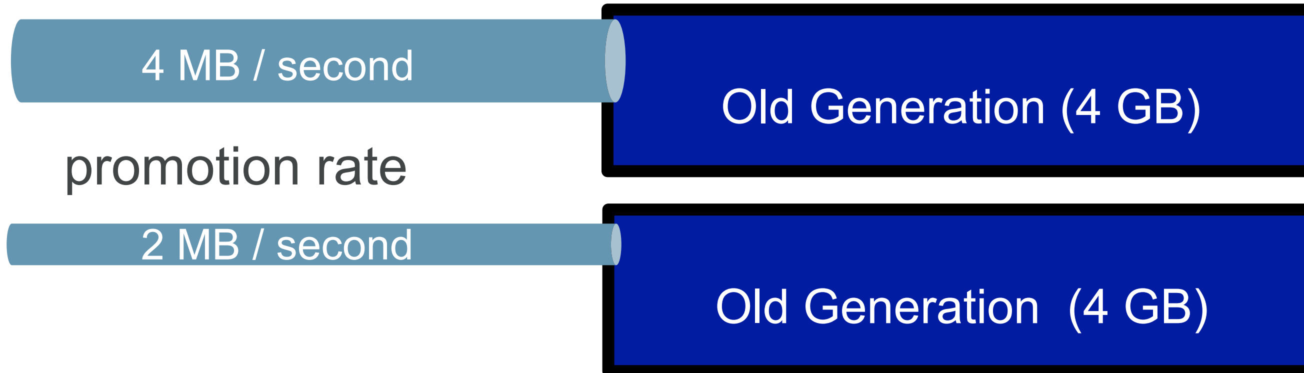
Influencing Old GC Frequency

Reduce promotion rate

- Old space fills more slowly with reduced object allocation rate



- Obvious, right? 2x drop in promotion rate, time to fill Old Generation space increases 2x, i.e. old GC frequency cut in ½

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Influencing Old GC Frequency

Make Old Generation size bigger (assuming same promotion rate)

Old Generation (4 GB)

Old Generation (8 GB)

- Same promotion rate, 2x increase in Old Generation space, time between GC increases 2x, i.e. Old GC frequency cut in ½

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Old GC Frequency

Consequences

- Reduce promotion rate
  - Lower injection rate or load on the application
    - Lower system throughput & system capacity, maybe better latency
  - Capture memory profiles and reduce promotions
    - Focus on object retention as much as, or more than object allocations (Look at java.util.LinkedList element removal)
    - Requires (development) work, and may be non-trivial
    - Throughput and latency may (or should) improve

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Old GC Frequency

Consequences

- Increase old generation size
  - Less frequent old GCs due to larger size
  - Likely higher throughput, and possibly lower latency due to less frequent application pauses or collection activity
    - All 3 are probably attractive
  - Worse case latency likely impacted for non-concurrent, or non mostly concurrent collectors
    - Hmmm … may be not so attractive?

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Old GC Frequency

Consequences of larger old gen space

- What about the potential impact with a concurrent, or mostly concurrent old generation collector ?
  - Less impact on available capacity due to less frequent collection activity
  - May see higher throughput and/or lower latency due to lower CPU cache eviction due to less frequent concurrent GC activity
  - Larger footprint due to larger old generation size

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Case Study: String Density

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String Density

JEP 254: Compact Strings

- JDK 9 feature
- More space-efficient internal representation for java.lang.String
- Terminology
  - String Density == Project name
  - Compact Strings == Feature name
- Goals
  - Lower memory footprint, yet no regression in throughput
    - Implied are no latency or CPU usage regressions

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String Density

What about the 3 legged stool ?!?!

Lots of work!

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String Density

What about the effort?

- 10 contributing engineers
  - 8 contributing from Oracle
  - 2 contributing from Intel
- Each spending about 1 year, ½ time on String Density
  - About 5 man years of effort

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String Density

Additional requirements

- Improve space efficiency for String and related classes
- Preserve throughput and latency
- Preserve compatibility
  - Java supports UTF-16, yet many apps only use lower byte in Strings
  - No new Java SE APIs, no changes required for upstream applications
- Replacement for JDK 6’s Compressed Strings
- Platforms: X86/X64, SPARC, ARM 32/64
- OS: Linux, Solaris, Windows and Mac OS X

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Analysis approach

- Repository of 950+ heap dumps from various Oracle FMW, Fusion Apps, and Java applications
  - How much can memory footprint be reduced?
- Java Object Layout tools
  - If fields added or removed from String class, what's the footprint impact per String instance?
- JVM model's analyzed; 32-bit, 64-bit w/ no compressed oops, 64-bit with compressed oops (8 byte aligned), and 64-bit with compressed oops (16 byte aligned)

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String Density

What we learned

- Distribution of the live data size similar across the models
  - Roughly 300 MB to 2.5 GB with a long tail
- char[]'s consume about 10% - 45% of the live data size
- Most Strings contain single byte chars
- 75% of Strings are 35 chars or smaller
  - Long tail distribution as the String sizes get larger beyond 35 chars
- 35% to 40% reduction in char[] footprint, not 50% theoretical reduction
- 5% - 15% reduction in application footprint

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String Density

Proposed solution

- Store chars in String as either UTF-16, or ISO-8859-1/Latin1
  - Stripping off leading zero byte of two byte UTF-16 char
- Use byte[] instead of char[] to store String's characters
  - 1 byte per char for ISO-8850-1/Latin1
  - 2 bytes per char for UTF-16
- Add an encoding byte field to indicate the encoding in use
  - Ability to extend to support additional character encodings

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Proposed solution continued …

- Strings with all leading byte bytes as 0
  - Candidate for ISO-8850-1/Latin1 encoding
  - Leading 0 bytes stripped off, and trailing bytes stored, i.e. single byte per char
- String with any leading byte in incoming char as non 0
  - Cannot be encoded as ISO-8859-1/Latin1, stored as UTF-16 encoded, i.e. two bytes per char
  - Compress (deflate) incoming characters, inflate to UTF-16 when returning sequence of chars via String API(s)

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Proposed solution continued …

- Why not UTF-8?

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String Density

Proposed solution continued …

- Why not UTF-8?
  - Cause we're stupid!

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String Density

Proposed solution continued …

- Why not UTF-8?
  - Cause we’re stupid! Just joking of course!!!
  - UTF-8 supports variable width characters
  - Many String operations require random access into sequence of chars
    - Their throughput performance would suffer!
  - UTF-8 encoding is great for character transmission
    - It’s not performant for String operations

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String Density

JDK 8 String class versus new JDK 9 String class

Old String Class (JDK 8)

```
{
    private final char value[];
    private int hash;
    ...
}
```

New String Class (JDK 9)

```
{
    private final byte[] value;
    private final byte coder;
    private int hash;
    ...
}
```


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What about memory footprint per String instance?

```
***** 32-bit VM: *****************************************************
java.lang.String object internals:
 OFFSET  SIZE   TYPE DESCRIPTION                    VALUE
      0     8        (object header)                N/A
      8     4 char[] String.value                   N/A
     12     4    int String.hash                    N/A
Instance size: 16 bytes (estimated, the sample instance is not available)
Space losses: 0 bytes internal + 0 bytes external = 0 bytes total

***** 64-bit VM: *****************************************************
java.lang.String object internals:
 OFFSET  SIZE   TYPE DESCRIPTION                    VALUE
      0    16        (object header)                N/A
     16     8 char[] String.value                   N/A
     24     4    int String.hash                    N/A
     28     4        (loss due to the next object alignment)
Instance size: 32 bytes (estimated, the sample instance is not available)
Space losses: 0 bytes internal + 4 bytes external = 4 bytes total
```


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String Density

What about memory footprint per String instance?

```
***** 64-bit VM, compressed references enabled: ***************************
java.lang.String object internals:
 OFFSET  SIZE   TYPE DESCRIPTION                    VALUE
      0    12        (object header)                N/A
     12     4 char[] String.value                   N/A
     16     4    int String.hash                    N/A
     20     4        (loss due to the next object alignment)
Instance size: 24 bytes (estimated, the sample instance is not available)
Space losses: 0 bytes internal + 4 bytes external = 4 bytes total

***** 64-bit VM, compressed references enabled, 16-byte align: ************
java.lang.String object internals:
 OFFSET  SIZE   TYPE DESCRIPTION                    VALUE
      0    12        (object header)                N/A
     12     4 char[] String.value                   N/A
     16     4    int String.hash                    N/A
     20    12        (loss due to the next object alignment)
Instance size: 32 bytes (estimated, the sample instance is not available)
Space losses: 0 bytes internal + 12 bytes external = 12 bytes total
```

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String Density

What about throughput?

- Developed **400** JMH micro-benchmarks for String APIs
  - Results
    - http://cr.openjdk.java.net/~thartmann/compact_strings/microbenchmarks
  - Micro-benchmarks (and various other String Density artifacts)
    - http://cr.openjdk.java.net/~shade/density/
- String is highly optimized using SIMD instructions
  - About 55 specific JIT compiler optimizations for String related operations
    - Non-trivial amount of work
    - Why not fly your own single byte String class?

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String Density

Macro-level performance

- SPECjbb2015 (Intel x64)
  - Live data size reduction of about 7% *(footprint reduction)*
  - Critical-jOps increased by about 11% *(latency maintained or improved)*
    - At critical-jOps, CPU utilization remained the same as baseline
  - Max-jOps increased by about 3% *(throughput improved)*
- SPECjbb2005 (Intel x64)
  - Live data size reduction of about 21%
  - Throughput increase of about 5%
  - 23% reduction in GC frequency

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String Density

Three legged stool revisited

- With a lot of effort ….
- We realized a reduction in memory footprint, yet able to maintain or improve throughput, and maintain latency or reduce latency
- And, able to maintain or improve system capacity

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Call to Action

Interested or Intrigued?

- Can’t wait to try it on your application(s) ?
  - Again, a JDK 9 feature
- Implementation:
  - Repository: http://hg.openjdk.java.net/jdk9/sandbox/
  - Branch: JDK-8054307-branch

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Call to Action

Interested or Intrigued?

- Build Steps:

```
$ hg clone http://hg.openjdk.java.net/jdk9/sandbox/
$ cd sandbox
$ sh ./get_source.sh
$ sh ./common/bin/hgforest.sh up -r JDK-8054307-branch
$ make configure
$ make images
```

- Command line option to enable/disable feature:

  -XX:+CompactStrings / -XX:-CompactStrings

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Main Takeaways

Raising all three legs of the performance stool is hard, but possible with a lot of non-trivial effort.

Reason about the tradeoffs in realizing improvements in one or two of the performance attributes, i.e. understand the alternatives, and realize system capacity may be a criteria that fits in here too.

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Acknowledgements

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  - Past and present members

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