Effective Software

Lecture 10: JVM - Memory Analysis, Data Structures, Collections for Performance

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[1] Oaks, S.: Java Performance: 2nd Edition. O'Reilly, USA 2020.
[2] JVM source code - http://openjdk.java.net
[3] Hylock, R.: Large-Scale Memory Efficient Java Primitive Collections. Journal of Software, March 2016.

Outline

- Memory analysis
  - Static memory analysis
    - Shallow vs. retained size
  - Dynamic memory analysis
- Data structures
  - Objects, Arrays
  - Auto-boxing, Unboxing
- Memory usage efficiency
  - Collections for performance
  - Collection resizing

JVM Performance Factors and Memory Analysis

» application **performance factors**

- total runtime
  - algorithms (complexity, instructions, synchronization)
  - memory management (garbage collection) overhead
  - **data structures** (speed of data access, cache efficiency, GC pressure)
- memory consumption
  - **data structures** (memory usage efficiency)

» **memory analysis**

- static memory analysis
  - analyze memory usage at given moment
  - suitable for data structure efficacy analysis, inspect content
- dynamic memory analysis
  - analyze dynamic changes over time
  - suitable for object allocation analysis and **memory leak** identification

Static Memory Analysis – Object Histogram

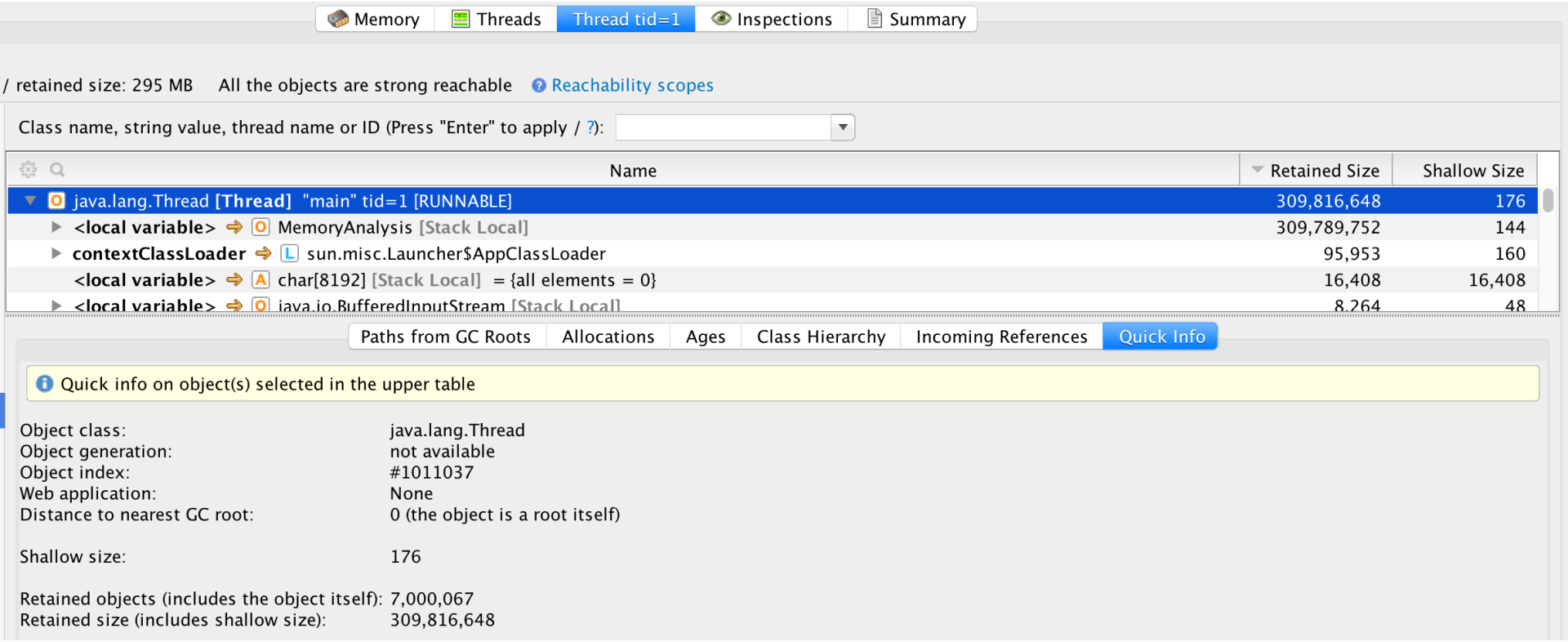
» analyze **histogram of objects** – imply global safepoint (stop the world)

- jmap -histo:live {PID}

num	#instances	#bytes	class name
1:	3000257	72006168	java.lang.Integer
2:	1000122	48005856	java.util.HashMap$Node
3:	1000012	40000480	java.util.LinkedList$Node
4:	1000000	40000000	gnu.trove.list.linked.TIntLinkedList$TIntLink
5:	2	33913088	[D
6:	162	24963896	[I
7:	1000001	24000024	java.lang.Double
8:	26	16781936	[Ljava.util.HashMap$Node;
9:	604	8056600	[Ljava.lang.Object;
10:	37	2176208	[B
11:	1549	184864	[C
12:	635	109344	java.lang.Class
13:	1519	48608	java.lang.String
14:	307	14736	java.util.concurrent.ConcurrentHashMap$Node
15:	108	12960	java.lang.reflect.Field
16:	85	8840	java.net.URL
17:	257	6168	java.lang.Byte
18:	257	6168	java.lang.Long
19:	257	6168	java.lang.Short
20:	123	5904	java.util.Hashtable$Entry
21:	102	5712	java.lang.ref.SoftReference
22:	5	4984	[Ljava.util.concurrent.ConcurrentHashMap$Node;
23:	284	4544	java.lang.Object

Static Memory Analysis – Heap Dump

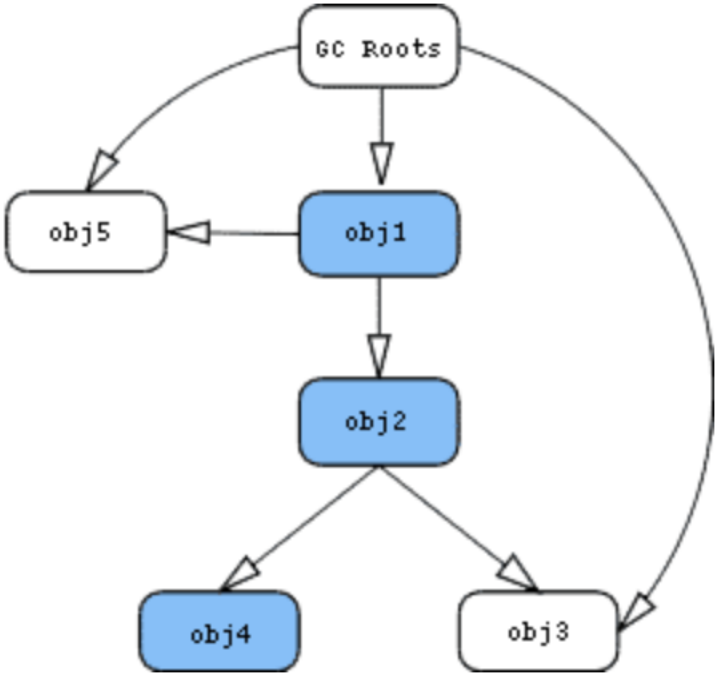
- capture **heap dump** – exported during global safepoint (stop the world)
  - -XX:+HeapDumpOnOutOfMemoryError
  - jmap -dump:live,format=b,file={name}.hprof {PID}
  - visualvm, yourkit, …
- analyze heap dump – visualvm, yourkit, …

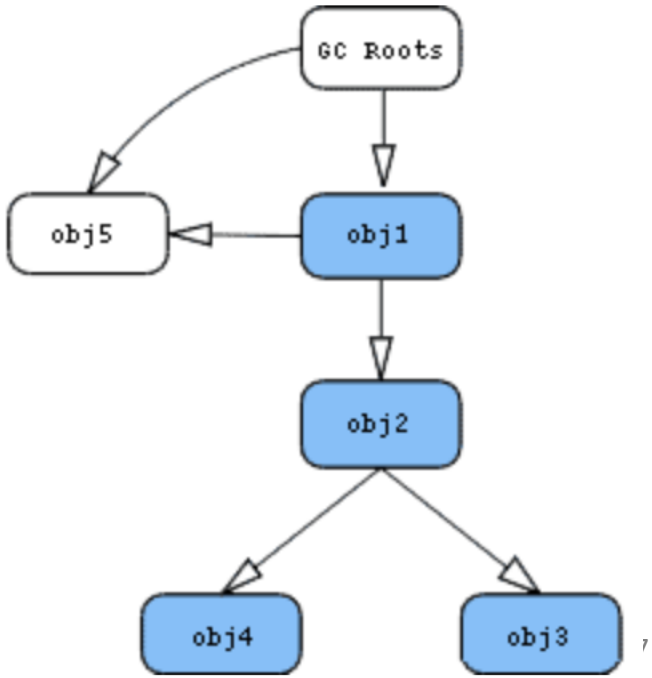


Shallow vs. Retained Size

» **shallow size**
- memory allocated to store object itself

» **retained size**
- quantity of memory this object preserves from GC clean-up
  - amount of memory freed if the object is GCed
- own shallow size + shallow size of all objects directly or indirectly accessible **ONLY** from this object





Static Analysis Advanced Inspections

» **wasting memory** – memory doesn't keep any useful content

- **duplicate strings**
  - share string instances via pooling or intern()
- **duplicate objects** – same field contents
  - share them, lazy creation, non-permanent usage
- **zero length arrays**
  - unnecessary load for GC
  - use per-class empty array singleton (e.g., via static field in the class)
- **null fields** - objects having a lot of 'null' fields
  - use subclasses for rarely assigned fields
- **sparse arrays** – big number of 'null', zero or same elements
  - use alternate data structures (e.g., maps or refactor algorithms)
- **inefficient data structure** – large overhead of useless content
  - use different data structures

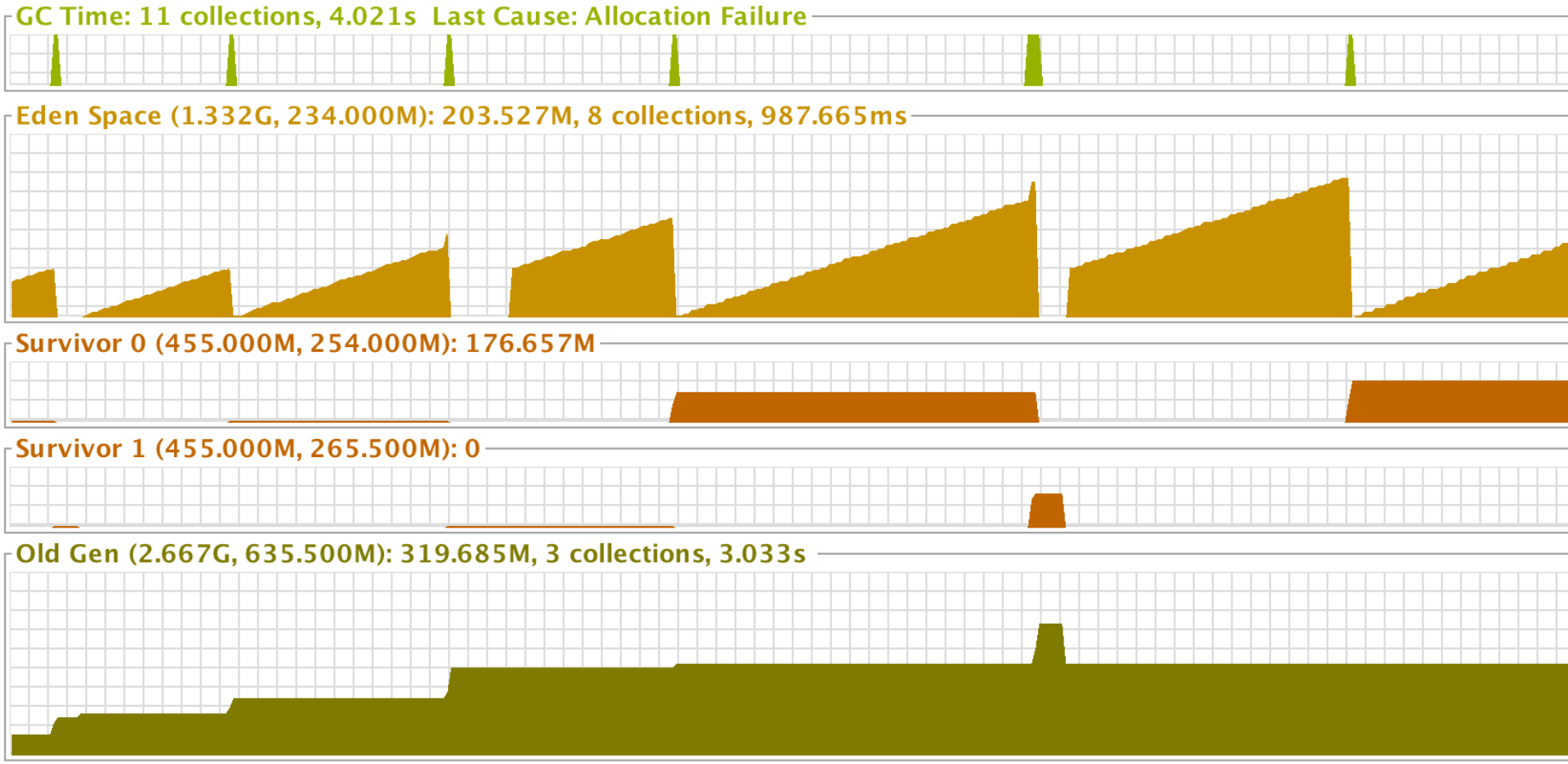
Static Analysis Advanced Inspections

- **memory leak** – objects are no longer used but there are still references to them
  - **object retained from inner non-static class back reference**
    - implicit back reference from inner class instance (even anonymous), e.g., used for callback objects
    - minimize usage of non-static inner class instances
- **performance** – speed of data read / write
  - **hash tables with non-uniformly distributed hash codes**
    - degraded performance due to hash collisions
    - use better hashCode implementation

Dynamic Memory Analysis – GC Telemetry

» analyze **GC telemetry** – e.g., visualvm with VisualGC plugin

- usage of Eden space in time
- GC collections and their duration
- not affecting performance of monitored application



Dynamic Memory Analysis – Heap Dumps

» compare **heap dumps**

- difference in object count and size in various application state
- dumps with all objects (not just live) can help analyze object allocations if there is no GC run in between
- each heap dump requires global safepoint (time depends on the heap size)

Old snapshot (the baseline): dump1
New snapshot: dump2 ← **this snapshot**

Objects
Classes
Classes and packages
Exceptions
Exceptions

Name	Objects (+/-)		Size (+/-)	
char[]	+5,386	+93 %	+407,040	+6 %
byte[]	+927	+16 %	+292,792	+5 %
jdk.internal.org.objectweb.asm.Item	+3,051	+53 %	+170,856	+3 %
jdk.internal.org.objectweb.asm.Item[]	+174	+3 %	+101,280	+2 %
java.lang.String	+3,219	+55 %	+77,256	+1 %
java.lang.Class[]	+1,275	+22 %	+38,456	+1 %
java.lang.Object[]	+716	+12 %	+34,984	+1 %
jdk.internal.org.objectweb.asm.MethodWriter	+132	+2 %	+29,568	+0 %
java.lang.invoke.MethodType	+729	+13 %	+29,160	+0 %
java.lang.invoke.MethodType$ConcurrentWeakInternSet$WeakEntry	+729	+13 %	+23,328	+0 %
jdk.internal.org.objectweb.asm.Label	+245	+4 %	+15,680	+0 %
java.lang.StringBuilder	+638	+11 %	+15,312	+0 %
jdk.internal.org.objectweb.asm.ClassWriter	+91	+2 %	+15,288	+0 %
java.lang.reflect.Method	+168	+3 %	+14,784	+0 %
jdk.internal.org.objectweb.asm.Type	+439	+8 %	+14,048	+0 %
jdk.internal.org.objectweb.asm.AnnotationWriter	+248	+4 %	+13,888	+0 %
jdk.internal.org.objectweb.asm.ByteVector	+562	+10 %	+13,488	+0 %
java.lang.StringBuffer	+457	+8 %	+10,968	+0 %
jdk.internal.org.objectweb.asm.Frame	+226	+4 %	+10,848	+0 %
java.lang.invoke.MemberName	+326	+6 %	+10,432	+0 %
boolean[]	+34	+1 %	+9,248	+0 %
java.lang.invoke.LambdaForm$Name[]	+130	+2 %	+5,984	+0 %
java.lang.invoke.InvokerBytecodeGenerator	+80	+1 %	+5,120	+0 %
java.lang.invoke.LambdaForm$BasicType[]	+88	+2 %	+4,120	+0 %
java.util.HashMap	+81	+1 %	+3,888	+0 %
jdk.internal.org.objectweb.asm.Type[]	+114	+2 %	+3,880	+0 %
java.util.AbstractList$Itr	+115	+2 %	+3,680	+0 %
java.util.HashMap$ValueIterator	+81	+1 %	+3,240	+0 %

Dynamic Memory Analysis – Allocation Tracking

» **allocation tracking** - **memory profiler**

- track every n-th object allocation (trade-off between precision and speed)
- affect performance of profiled application, injects **traceObjAlloc** byte code
  - introduce a lot of byte code + consume memory
  - decreases possibility of JIT optimizations

Call Tree	Objects		Size	
<Objects without allocation information>	92,413		12,760,600	
<All threads>	25,264	100 %	1,692,200	100 %
com.intellij.rt.execution.application.**AppMain.main**(String[])	25,264	100 %	1,692,200	100 %
NativeMethodAccessorImpl.java (native) **Lambda.main**(String[])	25,264	100 %	1,692,200	100 %
Lambda.java:44 **Lambda.reversedAlphabeticalOnlyOrder**(String[])	25,258	99 %	1,667,408	99 %
Lambda.java:13 java.lang.invoke.**MethodHandleNatives.linkCallSite**(Object, Object, Object, Object, Object, Object[])	15,709	62 %	1,050,728	62 %
Lambda.java:13 java.lang.invoke.**MethodHandleNatives.linkMethodHandleConstant**(Class, int, Class, String, Object)	5,627	22 %	324,184	19 %
Lambda.java:15 java.util.**Comparator.comparing**(Function)	1,557	6 %	106,040	6 %
Lambda.java:16 java.util.stream.**Collectors.toList**()	1,032	4 %	68,912	4 %
Lambda.java:16 java.util.stream.**ReferencePipeline.collect**(Collector)	869	3 %	71,760	4 %
Lambda.java:14 java.lang.invoke.**MethodHandleNatives.linkCallSite**(Object, Object, Object, Object, Object, Object[])	161	1 %	10,088	1 %
Lambda.java:13 java.lang.invoke.**MethodHandleNatives.findMethodHandleType**(Class, Class[])	98	0 %	5,904	0 %
Lambda.java:13 java.util.**Arrays.stream**(Object[])	87	0 %	17,608	1 %
Lambda.java:16 java.util.stream.**Collectors.<clinit>**()	33	0 %	3,608	0 %
Lambda.java:14 java.lang.invoke.**MethodHandleNatives.linkMethodHandleConstant**(Class, int, Class, String, Object)	24	0 %	872	0 %
Lambda.java:14 java.lang.invoke.**MethodHandleNatives.findMethodHandleType**(Class, Class[])	18	0 %	640	0 %

Classes | Packages | Object Explorer | Generations | Ages | Reachability | Class Loaders | Web Applications | Callees List | Quick Info

Class list for objects selected in the upper table

Class	Objects		Shallow Size		Retained Size	
char[]	5,280	21 %	388,472	23 %	388,472	23 %
byte[]	929	4 %	284,856	17 %	284,856	17 %
jdk.internal.org.objectweb.asm.Item	3,051	12 %	170,856	10 %	170,856	10 %
java.lang.Class	230	1 %	136,328	8 %	165,824	10 %

Dynamic Memory Analysis – Allocation Tracking

» **allocation tracking** – **flight recording** using jmc – no byte code instrumentation
  - identify large object allocations outside TLAB (thread local allocation buffer)

General | Allocation in New TLAB | Allocation Outside TLABs

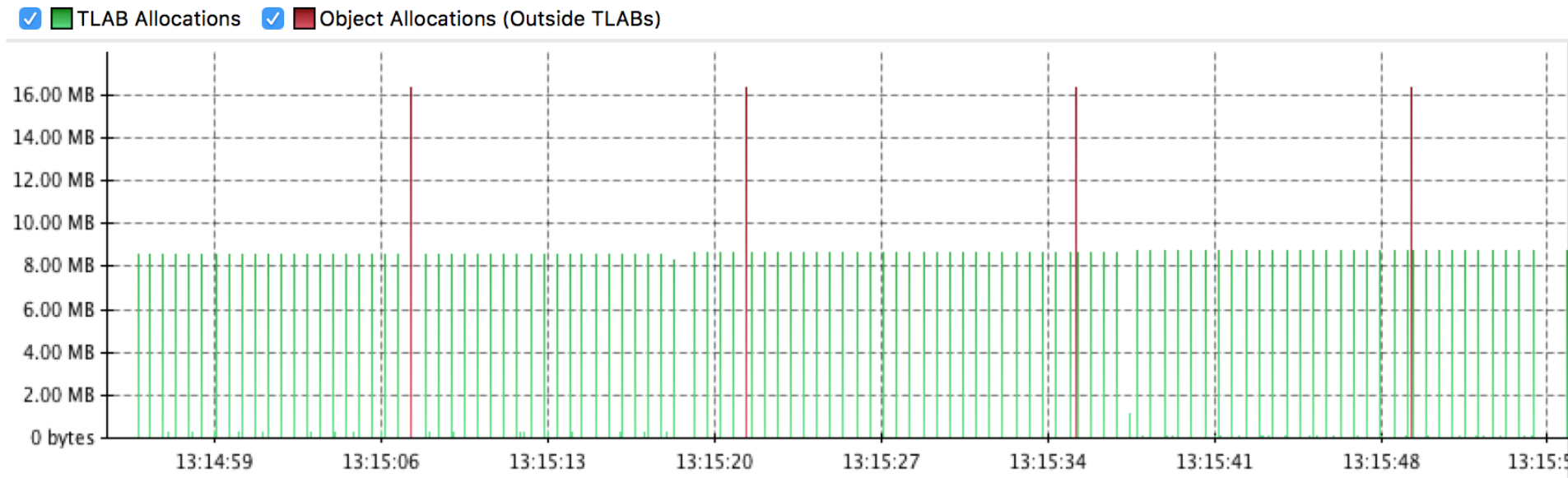
Thread Local Allocation Buffer (TLAB) Statistics

TLAB Count	393
Maximum TLAB Size	16.26 MB
Minimum TLAB Size	2.05 kB
Average TLAB Size	2.45 MB
Total Memory Allocated for TLABs	961.48 MB
Allocation Rate for TLABs	15.65 MB/s

Statistics for Object Allocations (Outside TLABs)

Object Count	48
Maximum Object Size	16.34 MB
Minimum Object Size	24 bytes
Average Object Size	5.67 MB
Total Memory Allocated for Objects	272.12 MB
Allocation Rate for Objects	4.43 MB/s

Allocation



Dynamic Memory Analysis – Allocation Tracking

» **allocation tracking** – **flight recording** using jmc – no byte code instrumentation

- identify large object allocations outside TLAB (thread local allocation buffer)

General | Allocation in New TLAB | Allocation Outside TLABs

Allocation by Class | Allocation by Thread | Allocation Profile

Allocation Pressure

Class	Average Object Si:	TLABs	Total TLAB Size
java.lang.Integer	24 bytes	38	325.76 MB
java.util.HashMap$Node	48 bytes	39	306.85 MB
java.lang.Double	24 bytes	15	128.52 MB
gnu.trove.list.linked.TIntLinkedList$TIntLink	40 bytes	14	119.89 MB
java.util.LinkedList$Node	40 bytes	5	43.15 MB
java.lang.Object[]	159.71 kB	49	21.43 MB
java.io.ObjectStreamClass$WeakClassKey	56 bytes	35	2.12 MB
char[]	128 bytes	40	1.94 MB
java.lang.Class	160 bytes	1	1.82 MB

Stack Trace

Stack Trace	TLABs	Total TLAB Size	Pressure
java.util.ArrayList.<init>(int)	1	16.26 MB	75.89%
java.util.AbstractCollection.toArray()	1	1.82 MB	8.49%
java.io.ObjectOutputStream.defaultWriteFields(Object, ObjectStreamClass)	17	1.32 MB	6.17%
java.io.ObjectOutputStream$HandleTable.growEntries()	11	1.27 MB	5.94%
sun.management.MemoryUsageCompositeData.getCompositeData()	4	171.98 kB	0.78%
sun.reflect.misc.MethodUtil.invoke(Method, Object, Object[])	3	164.10 kB	0.75%
java.io.ObjectStreamClass.invokeWriteObject(Object, ObjectOutputStream)	2	71.89 kB	0.33%
java.io.ObjectInputStream$HandleTable.<init>(int)	1	64.12 kB	0.29%
java.lang.reflect.Array.newInstance(Class, int)	1	64.05 kB	0.29%
sun.management.MappedMXBeanType$MapMXBeanType.toOpenTypeData(Object)	1	52.48 kB	0.24%

Dynamic Memory Analysis – Allocation Tracking

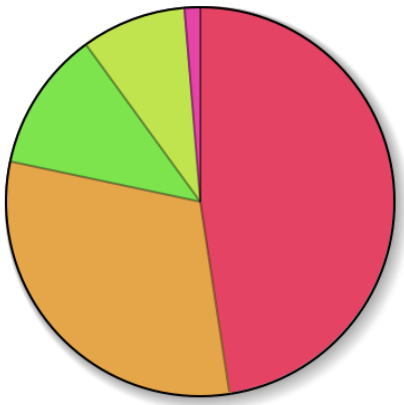
» **allocation tracking** – **flight recording** using jmc – no byte code instrumentation

- identify large object allocations outside TLAB (thread local allocation buffer)

General | Allocation in New TLAB | Allocation Outside TLABs

Allocation by Class | Allocation by Thread | Allocation Profile

Allocation Pressure



Class	Objects	Total Size	Pressure
double[]	8	129.37 MB	47.54%
int[]	14	83.76 MB	30.78%
java.util.HashMap$Node[]	2	32.00 MB	11.76%
java.lang.Object[]	10	22.90 MB	8.42%
byte[]	4	4.09 MB	1.50%
java.util.TreeMap$Entry	4	256 bytes	0.00%
java.util.TreeMap	2	160 bytes	0.00%
char[]	1	128 bytes	0.00%
java.util.TreeMap$KeyIterator	1	56 bytes	0.00%
java.lang.Integer	1	24 bytes	0.00%

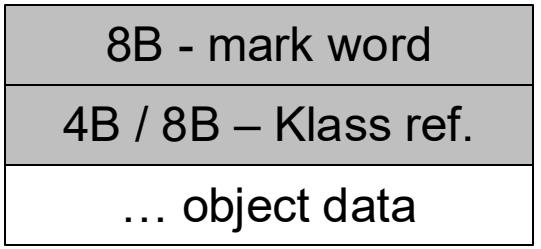
Stack Trace

Stack Trace	Objects	Total Size	Pressure
gnu.trove.impl.hash.TIntDoubleHash.setUp(int)	4	32.68 MB	39.02%
it.unimi.dsi.fastutil.ints.Int2DoubleOpenHashMap.<init>(int, float)	4	32.00 MB	38.20%
it.unimi.dsi.fastutil.ints.IntArrayList.<init>(int)	4	15.26 MB	18.22%
gnu.trove.list.array.TIntArrayList.<init>(int, int)	1	3.81 MB	4.55%
java.io.ObjectOutputStream$HandleTable.growEntries()	1	1.40 kB	0.00%

Data Structures – Primitives and Objects

- **primitives**: boolean(1), byte(1), char(2), int(4), long(8), float(4), double(8)
  - without implicit allocation
  - stored in variables or operand stack in JVM frame
- **objects** (object header structure overhead) allocated on the heap
  - every object is descendant of Object by default
    - methods – clone(), equals, getClass(), hashCode(), wait(…), notify (…), finalize()
  - objects for primitives: Boolean, Byte, Character, Integer, Long, Float, Double; can be **null**
  - objects with multiple fields use **type group alignment** and padding in the following order (in the same type group respecting declaration order):
    - longs and doubles (8B)
    - ints and floats (4B)
    - shorts and chars (2B)
    - bytes and booleans
    - references (4B / 8B)

Object structure (64-bit JVM):
- header 12 or 16 Bytes
- object data super class first



Data Structures – Object Example 64-bit <32GB Heap

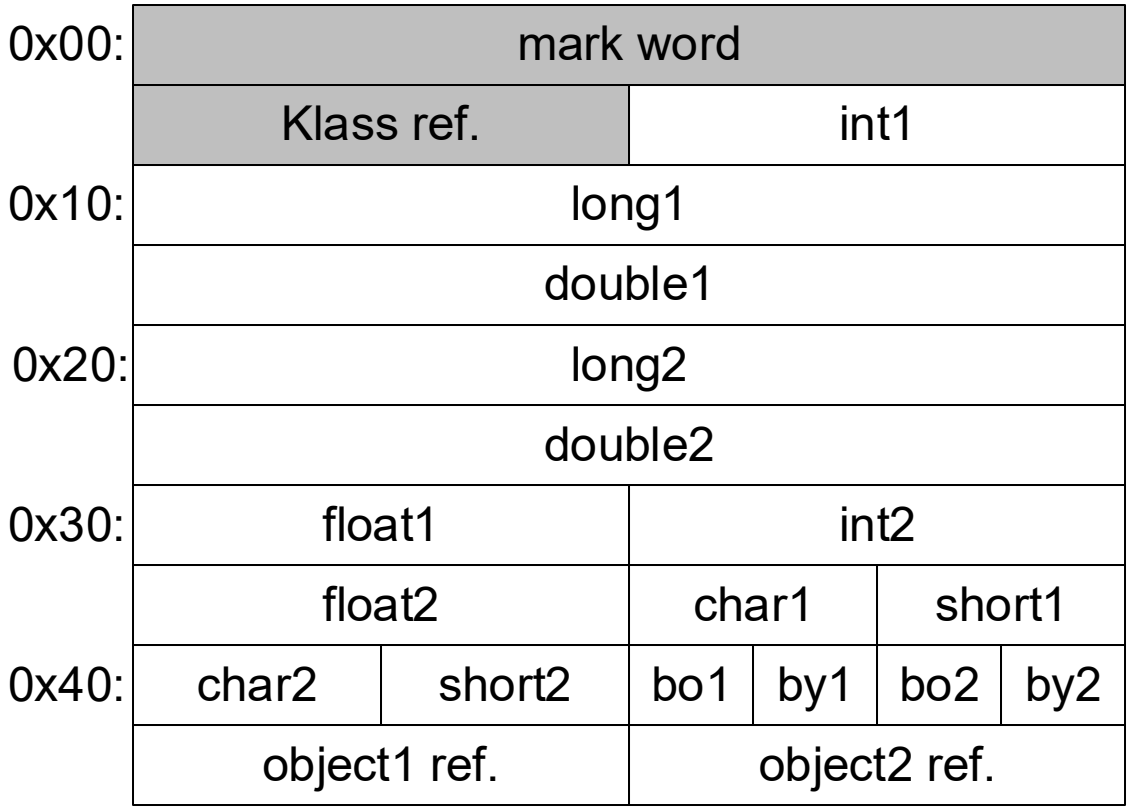
```
class Structure {
    private boolean boolean1;
    private byte byte1;
    private char char1;
    private short short1;
    private int int1;
    private long long1;
    private float float1;
    private double double1;
    private Object object1;
    private boolean boolean2;
    private byte byte2;
    private char char2;
    private short short2;
    private int int2;
    private long long2;
    private float float2;
    private double double2;
    private Object object2;

    Structure(int value, Object ref

    @Override
    public String toString() {...}
}
```

Object structure (64-bit JVM) **using compressed OOP**:

- object size 80 Bytes



Data Structures – Object Example 64-bit >=32GB Heap

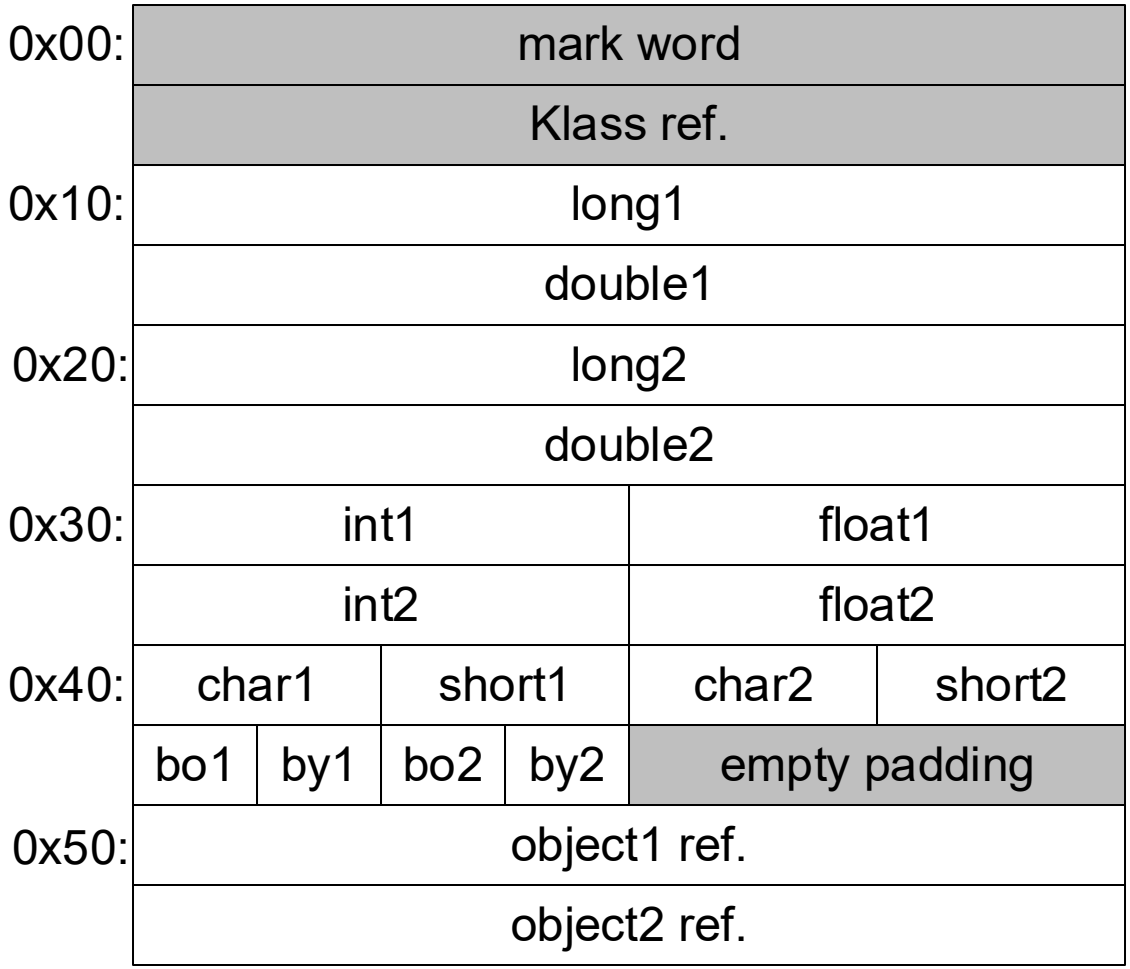
```
class Structure {
    private boolean boolean1;
    private byte byte1;
    private char char1;
    private short short1;
    private int int1;
    private long long1;
    private float float1;
    private double double1;
    private Object object1;
    private boolean boolean2;
    private byte byte2;
    private char char2;
    private short short2;
    private int int2;
    private long long2;
    private float float2;
    private double double2;
    private Object object2;

    Structure(int value, Object ref

    @Override
    public String toString() {...}
}
```

Object structure (64-bit JVM) **using standard OOP**:

- object size 96 Bytes **(+20% vs. previous)**



Data Structures – Arrays

» **single-dimension arrays**

- special data structure which store several items of the same type in linear order; have the defined limit
- JAVA automatically check limitations
- allocated on the heap
- primitives – keep primitive values stored directly
- objects – keep references to objects (4B or 8B references)

» **multi-dimensional arrays**

- arrays of arrays - ragged array (non-uniform sub-level lengths)
- slower access due to dereferencing (multiple memory read operations) and multi-index bound checks
- consider **flatten array**

Array object structure (64-bit JVM):

- header 16 or 20 Bytes
- sequence of array values

8B - mark word
4B / 8B – Klass ref.
4B – array length
sequence of values

Memory Efficiency – Objects for Primitives

» **memory efficiency** – 100% efficiency means zero overhead

$$\frac{useful\_content\_size}{retained\_size} * 100[\%]$$

» correlates with **cache efficacy**

- cache line – read always consecutive 64 B of memory

» **data locality** further speed-up processing utilizing already cached data

Object	Useful size	Retained size (Efficiency) <32GB heap	Retained size (Efficiency) >=32GB heap
Boolean	1 bit	16 B (0.78 %)	24 B (0.52 %)
Byte	1 B	16 B (6.25 %)	24 B (4.17 %)
Short, Character	2 B	16 B (12.50 %)	24 B (8.34 %)
Integer, Float	4 B	16 B (25.00 %)	24 B (16.67 %)
Long, Double	8 B	24 B (33.34 %)	24 B (33.34 %)

Objects for Primitives

- **auto boxing** and **un-boxing** during assignment and parameter passing
  - valueOf({primitive}) and {primitve}Value() methods
- all objects for primitives are **immutable** (final values)
- beware of **inefficiencies** caused by auto boxing and un-boxing

```
public class PrimitiveObject {
    private static Integer integer = 0;

    public static void main(String[] args) {
        integer++;
    }
}
static {};
  Code:
     0: iconst_0
     1: invokestatic  #4
     4: putstatic     #2
     7: return

public static void main(java.lang.String[]);
  Code:
     0: getstatic     #2
     3: invokevirtual #3
     6: iconst_1
     7: iadd
     8: invokestatic  #4
    11: putstatic     #2
    14: return
```

```
private static Integer integer = 0;

// Method java/lang/Integer.valueOf:(I)Ljava/lang/Integer;
// Field integer:Ljava/lang/Integer;
```

```
integer++;
// Field integer:Ljava/lang/Integer;
// Method java/lang/Integer.intValue:()I


// Method java/lang/Integer.valueOf:(I)Ljava/lang/Integer;
// Field integer:Ljava/lang/Integer;
```

Conversion Inefficiencies - Example

» count word histogram

```
public static void main(String[] args) {
    Map<String, Integer> m = new TreeMap<String, Integer>();
    for (String word : args) {
        Integer freq = m.get(word);
        m.put(word, (freq == null ? 1 : freq + 1));
    }
    System.out.println(m);
}
```

Conversion Issues - Example

```
int i = 2;
int j = 2;
ArrayList<Integer> list = new ArrayList<Integer>();
list.add(i);
list.add(j);
System.out.printf(Boolean.toString(i==j));
System.out.printf(Boolean.toString(list.get(0)==list.get(1)));
System.out.printf(Boolean.toString(list.get(0).equals(list.get(1))));
```

» what is the output? and what is the output for i=2000 and j=2000 ?

Conversion Issues - Example

```
int i = 2;
int j = 2;
ArrayList<Integer> list = new ArrayList<Integer>();
list.add(i);
list.add(j);
System.out.printf(Boolean.toString(i==j));
System.out.printf(Boolean.toString(list.get(0)==list.get(1)));
System.out.printf(Boolean.toString(list.get(0).equals(list.get(1))));
```

» what is the output? and what is the output for i=2000 and j=2000 ?

true	true
true	false
true	true

Note: after serialization, the second is always false

Objects for Primitives – Identity Semantics

» **identity semantics** using cache for **valueOf({primitive})**
  - Short, Integer, Long – caches <-128;+127>
  - Byte – caches all values
  - Character – caches <0;+127>

» **not working** for objects created by constructor (e.g., new Integer(1))

```
private static class ShortCache {
    private ShortCache(){}

    static final Short cache[] = new Short[-(-128) + 127 + 1];

    static {
        for(int i = 0; i < cache.length; i++)
            cache[i] = new Short((short)(i - 128));
    }
}
public static Short valueOf(short s) {
    final int offset = 128;
    int sAsInt = s;
    if (sAsInt >= -128 && sAsInt <= 127) { // must cache
        return ShortCache.cache[sAsInt + offset];
    }
    return new Short(s);
}

public short shortValue() {
    return value;
}
```

Memory Efficiency – Java Collections

- **LinkedList<E>**
  - uses Node<E> object with bi-directional links
- **ArrayList<E>**
  - backend elementData array with references to objects
- **HashMap<K,V>**
  - backend hash table of Node<K,V> with cached hashCode and linked collisions

Note: Measured for 1 million of elements in Collections and Map

Object	Useful size	Retained size (Efficiency) <32GB heap	Retained size (Efficiency) >=32GB heap
LinkedList<Integer>	4 MiB	34.33 MiB (11.65 %)	47.26 MiB (8.46 %)
ArrayList<Integer>	4 MiB	17.73 MiB (22.56 %)	25.72 MiB (15.55 %)
HashMap<Integer,Double>	12 MiB	70.19 MiB (17.10 %)	87.67 MiB (13.69 %)

Collections for Performance

» **Trove** – Lesser GNU Public License (LGPL)

» **FastUtil** – Apache License 2.0

» **collections for performance**

- **type-specific** maps, sets, lists and queues
  - remove overheads related to auto-boxing and un-boxing
- small memory footprint
  - much better caching
  - sequential access is very fast
- fast access and insertion
- use **open addressing** hashing in Maps instead of chaining approach
- support big collections (>2^{31} elements) in *FastUtil*
- support custom hashing strategies in *Trove*

```
char[] foo, bar;
foo = new char[] {'a','b','c'};
bar = new char[] {'a','b','c'};
System.out.println(foo.hashCode() == bar.hashCode() ? "equal" : "not equal");
System.out.println(foo.equals(bar) ? "equal" : "not equal");
```

Open Addressing Hash Table

- **eliminates** the need for Map.Entry<K,V> **wrapper** supporting chaining
  - typed keys & values arrays
  - state byte array – FREE, FULL, REMOVED (*Trove*, total 3 arrays)
  - special 0/null key tracking + default return value for empty (*FastUtil*, total 2 arrays)
- smaller load factor implies less conflicts (*Trove* 0.5, *FastUtil* 0.75)
- **collision resolution** scheme
  - linear probing (*FastUtil*) – better cache utilization due to data locality
  - double hash probing (Trove) – less conflicts

$$h(i,k) = \left(h_1(k) + i \cdot h_2(k)\right) \bmod |T|$$

    - h_2 cannot be 0
- complex **deletion** to keep conflict searching consistent
  - shift last collision element instead of removed (*FastUtil*)
  - keep removed elements – used by later puts (*Trove*)
- usage of **prime number** size of hash table reduce hashing collisions (*Trove*)
- usage of **power of two** size of hash table leads to fast bit operations (*FastUtil*)

Memory Efficiency – Collections for Performance

Note: 1 million of elements stored

Object	Useful size	Retained size (Efficiency) <32GB heap	Retained size (Efficiency) >=32GB heap
LinkedList<Integer>	4 MiB	34.33 MiB (11.65 %)	47.26 MiB (8.46 %)
TIntLinkedList *(Trove)*	4 MiB	20.60 MiB (19.42 %)	24.54 MiB (13.54 %)
ArrayList<Integer>	4 MiB	17.73 MiB (22.56 %)	25.72 MiB (15.55 %)
TIntArrayList *(Trove)*	4 MiB	~4.00 MiB (~100.00 %)	~4.00 MiB (~100.00%)
IntArrayList *(FastUtil)*	4 MiB	~4.00 MiB (~100.00 %)	~4.00 MiB (~100.00%)
HashMap<Integer,Double>	12 MiB	70.19 MiB (17.10 %)	87.67 MiB (13.69 %)
TIntDoubleHashMap *(Trove)*	12 MiB	27.85 MiB (43.09 %)	27.85 MiB (43.09 %)
Int2DoubleOpenHashMap *(FastUtil)*	12 MiB	25.17 MiB (47.68 %)	25.17 MiB (47.68 %)

Collection Resizing – Default Expected Capacity

- **run-time inefficiencies** caused by collection resizing
  - explicitly specify expected collection capacity
- **ArrayList**
  - shared static default empty backend array
  - backend array default capacity 10 (allocated during first add)
  - grow implies copy of all previous elements - strategy +~50%
  - no automatic shrinking, manual using trimToSize
- **TIntArrayList** (Trove)
  - backend array default capacity 10 (allocated immediately)
  - grow implies copy of all previous elements - strategy *2
  - no automatic shrinking, manual using trimToSize
- **IntArrayList** (FastUtil)
  - backend array default capacity 16 (allocated immediately)
  - grow implies copy of all previous elements - strategy *2
  - no automatic shrinking, manual using trim

Collection Resizing – Default Expected Capacity

- **HashMap**
  - hash table initialized with the first element
  - default hash table size 16 (default load factor 0.75)
    - custom capacity rounded to power of two
  - grow implies re-hashing (iteration + puts) of all previous elements
    - strategy *2
  - hash table shrinking not supported at all
- **TIntDoubleHashMap** (Trove)
  - default hash table size 23 (default load factor 0.5)
    - custom capacity adjusted to nearest bigger prime number
  - grow implies re-hashing (iteration + puts) of all previous elements
    - strategy nearest bigger prime number for size * 2
  - auto compaction after certain number of removals
    - nearest bigger prime number for the currently stored elements
    - can be temporarily disabled if you are planning to do a lot of removals

Collection Resizing – Default Expected Capacity

» **Int2DoubleOpenHashMap** (FastUtil)
- backend arrays allocated immediately
- default hash table size 16 (default load factor 0.75)
  - custom capacity rounded to power of two
- grow implies re-hashing (iteration + puts) of all previous elements
  - strategy *2
- auto shrinking after remove if used less than ¼ - strategy :2
  - not shrinking under minimum hash table size 16

» **further optimizations** possible
- use stubs for no/one element collections when your application contains a lot of collections