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java.lang.String Catechism

Stay Awhile And Listen

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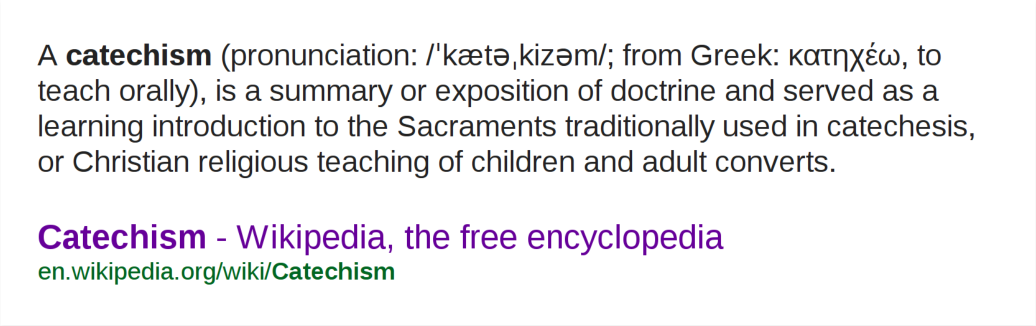
Intro



A **catechism** (pronunciation: /ˈkætəˌkizəm/; from Greek: κατηχέω, to teach orally), is a summary or exposition of doctrine and served as a learning introduction to the Sacraments traditionally used in catechesis, or Christian religious teaching of children and adult converts.

Catechism - Wikipedia, the free encyclopedia
en.wikipedia.org/wiki/**Catechism**

“Science replaces private prejudice with public, verifiable evidence.”

— Richard Dawkins

Intro: Disclaimers

All tests are done:

- ...by trained professionals: recheck[1] the results before using them
- ...on 1x2x4 i7-4790K (4.0 GHz, HSW): that machine is **fast**
- ...running Linux x86_64, 3.13: latest stable Linux Kernel
- ...with a 8u40 EA x86_64: the latest and greatest JDK
- ...driven by JMH[2]: the latest and greatest benchmarking harness

[1] https://github.com/shipilev/article-string-catechism/

[2] http://openjdk.java.net/projects/code-tools/jmh/

Intro: Strings are abundant

- Humans communicate with text
- Machines follow suit and communicate with text as well: most source code is text, many data interchange formats are text

- Anecdotal data from JEP 192: 25% of heap occupied by String objects
- Anecdotal data: String optimizations usually bring the immediate payoff

Understanding and avoiding cardinal sins is the road to awe.

Internals

Internals: java.lang.String inside

```
public final class String implements ... {
  private final char[] value;
  private int hash;
  ...
```

Strings are immutable:

- Can use/pass them without synchronization, and nothing breaks
- Can share the underlying `char[]` array, covertly from user

Internals: java.lang.String internals

Quite a bit of space overhead:

```
java.lang.String object internals:
 OFFSET  SIZE   TYPE DESCRIPTION
      0    12        (object header)
     12     4 char[] String.value
     16     4    int String.hash
     20     4        (alignment loss)
Instance size: 24 bytes
```

- 8..16 bytes: `String` header
- 4..4 bytes: `String` hashcode
- 12..16 bytes: `char[]` header
- 0..8 bytes: alignment losses

12..24 bytes against `char[]`, 24..44 bytes against `wchar_t*`

Internals: Catechism

Q: Should I use `Strings` to begin with?
A: Absolutely, when you are dealing with text data.

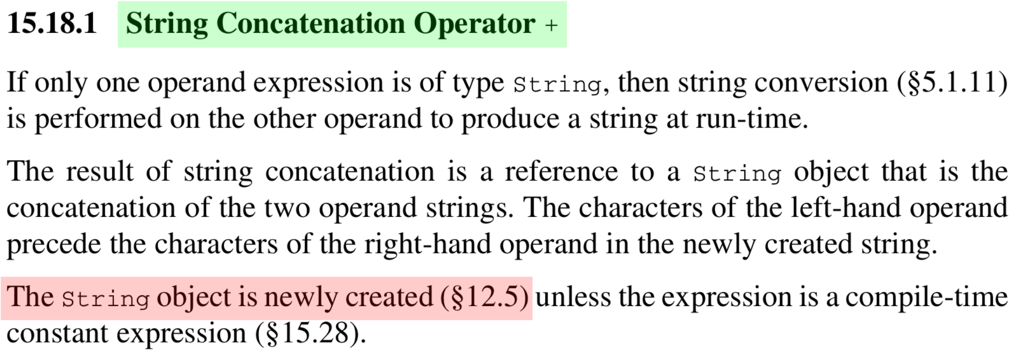
Q: What if memory footprint is a concern?
A: There are remedies for that, read on.

Q: I can wind up my own `String` implementation over `char[]`!
A: Sure you can, read on for caveats.

Q: *Should* I wind up my own `String` implementation?
A: *(Silence was the answer, and Engineer left enlightened)*

Immutable

Immutable: Strings are special



15.18.1 String Concatenation Operator +

If only one operand expression is of type `String`, then string conversion (§5.1.11) is performed on the other operand to produce a string at run-time.

The result of string concatenation is a reference to a `String` object that is the concatenation of the two operand strings. The characters of the left-hand operand precede the characters of the right-hand operand in the newly created string.

The `String` object is newly created (§12.5) unless the expression is a compile-time constant expression (§15.28).

Immutable: Stuck In A Loop

```
@Benchmark
public String string() {
  String s = "Foo";
  for (int c = 0; c < 1000; c++) {
    s += "Bar";
  }
  return s;
}
```

Immutable: Stuck In A Loop

```
@Benchmark
public String string() {
  String s = "Foo";
  for (int c = 0; c < 1000; c++) {
    s += "Bar"; // newly created String here
  }
  return s;
}
```

Immutable: Stuck In A Loop

```
@Benchmark
public String stringBuilder() {
  StringBuilder sb = new StringBuilder();
  for (int c = 0; c < 1000; c++) {
    sb.append("Bar");
  }
  return sb.toString();
}
```

Immutable: Stuck In A Loop

How bad could it be, anyway?

Benchmark	Throughput, ops/s	
string	3250.875	± 18.434
stringBuffer	125270.620	± 1005.263
stringBuilder	116173.291	± 422.926

Lots of pain: here, 30x performance penalty for adding a thousand of Strings.
Compilers are only able to help so much (more later).
My JVM hovercraft is full of GC eels.

Immutable: Catechism

Q: Why this is so painful?
A: Immutability **almost always** comes at a cost.

Q: But I like immutability, how to ease the pain?
A: Use Builders to construct immutable objects.

Q: Why can't JDK/JVM optimize this for us?
A: It can, in many cases. But, there is no escape if you want the best possible performance for all possible cases. (No Free Lunch)

Q: Do I need the best possible performance?
A: *(Silence was the answer, and Engineer left enlightened)*

Concat

Concat: Decompiling

```java
@Benchmark
public String string_2() {
  return s1 + s2;
}
```

...compiles into:

```
public String string_2();
  Code:
     0: new             #14    // java.lang.StringBuilder
     3: dup
     4: invokespecial #15    // StringBuilder.new()
     7: aload_0
     8: getfield        #3     // s1:String;
    11: invokevirtual #16    // StringBuilder.append(String);
    14: aload_0
    15: getfield        #5     // s2:String;
    18: invokevirtual #16    // StringBuilder.append(String);
    21: invokevirtual #17    // StringBuilder.toString();
    24: areturn
```

SB: Decompiling

Not suprisingly,
`StringBuilder.append` chains are routinely optimized:

```
@Benchmark
public String sb_6() {
  return new StringBuilder()
      .append(s1).append(s2).append(s3)
      .append(s4).append(s5).append(s6)
      .toString();
}

@Benchmark
public String string_6() {
  return s1 + s2 + s3 + s4 + s5 + s6;
}
```

Try this with `-XX:±OptimizeStringConcat` to quantify...

SB: StringBuilder opts are good!

Benchmark	N	Score, ns/op				Impr
		-Opt		+Opt		
stringBuilder	1	13.993	± 0.079	8.694	± 0.080	+61%
stringBuilder	2	20.259	± 0.181	12.042	± 0.370	+68%
stringBuilder	3	27.015	± 0.224	14.831	± 0.068	+82%
stringBuilder	4	33.344	± 0.546	21.068	± 0.087	+58%
stringBuilder	5	38.151	± 0.216	25.454	± 0.122	+50%
stringBuilder	6	69.626	± 1.042	29.856	± 0.221	+133%
string	1	2.273	± 0.013	2.273	± 0.004	0%
string	2	20.410	± 0.150	11.793	± 0.055	+73%
string	3	27.059	± 0.311	14.897	± 0.075	+82%
string	4	32.952	± 0.446	21.122	± 0.177	+56%
string	5	37.978	± 0.321	25.349	± 0.141	+50%
string	6	70.134	± 0.728	29.895	± 0.334	+135%

SB: Implicit SB vs. Explicit Conversion

Because of that, people are surprised how this benchmark behaves:

```
private int x;

@Setup
void setup() { x = 1709; }

@Benchmark
String concat_Pre()      { return "" + x; }

@Benchmark
String concat_Post()     { return x + ""; }

@Benchmark
String integerToString() { return Integer.toString(x); }

@Benchmark
String stringValueOf()   { return String.valueOf(x); }
```

SB: Implicit SB vs. Explicit Conversion (cont.)

Benchmark	Score, ns/op	
concat_Post	14.962	± 0.136
concat_Pre	15.063	± 0.198
integerToString	21.824	± 0.181
stringValueOf	21.979	± 0.312

Implicit concatenation is faster than **explicit** conversions?

- `StringBuilder` optimizations kick in, and `append(int)` is actually faster!
- And will be slower with `-XX:-OptimizeStringConcat`

SB: Side Effects

Let’s make it a little bit more complicated...

```
private int x;

@Setup
void setup() { x = 1709; }

@Benchmark
String concat_just()          { return "" + x; }

@Benchmark
String concat_side()          { x--; return "" + (x++); }

@Benchmark
String integerToString_just() { return Integer.toString(x); }

@Benchmark
String integerToString_side() { x--; return Integer.toString(x++); }
```

SB: Side Effects (cont.)

Benchmark	Score, ns/op	
concat_just	14.868	± 0.057
integerToString_just	21.684	± 0.094
stringValueOf_just	21.622	± 0.090
concat_side	27.263	± 0.262
integerToString_side	21.625	± 0.093
stringValueOf_side	21.682	± 0.138

- Once we have a side-effect in `append()` call, optimization bails out[3]
- On deopt, need to «unwind» the execution, but unable to do so for stores
- Moving the memory stores out of `append()` args helps

[3] https://bugs.openjdk.java.net/browse/JDK-8043677

Lazy Logging: Trouble

```java
private int x;
private boolean enabled;

void log(String msg) {
  if (enabled) {
    System.out.println(msg);
  }
}

@Benchmark
void heap_string() {
  log("Wow,␣x␣is␣such␣" + x + "!");
}

@Benchmark
void heap_string_guarded() {
  if (enabled) {
    log("Wow,␣x␣is␣such␣" + x + "!");
  }
}
```

- Concatenation happens before the `enabled` check
- Wasting precious time constructing the strings we don't care about
- Therefore, most people opt to guard the logger calls before even touching the strings

Lazy Logging: Trouble

```
private int x;
private boolean enabled;

@Benchmark
void heap_lambda() {
  log(() -> "Wow,␣such␣" + x + "!");
}

@Benchmark
void noArg_lambda() {
  log(() -> "Such␣message,␣wow.");
}

@Benchmark
public void local_lambda() {
  int lx = x;
  log(() -> "Wow,␣such␣" + lx + "!");
}
```

- We can do much better with lambdas: deferred execution without a syntactic mess
- There is a bit of the underlying difference when referencing locals, fields, or nothing

Lazy Logging: Lazy Logging

Method	Time, ns/op		
	heap	local	noArgs
string	19.298 ± 0.399	17.718 ± 0.248	0.381 ± 0.007
lambda	1.893 ± 0.011	1.809 ± 0.019	0.385 ± 0.013
string_guarded	0.385 ± 0.010	0.381 ± 0.004	0.383 ± 0.007

Lambdas rock! The explicit guard still wins, but not by a large margin: capturing lambdas (yet) need instantiation.

Concat: Catechism

Q: Should I be worried about concatenation costs?
A: You should in all non-trivial cases. You can't help much in trivial cases.

Q: What concatenation cases are non-trivial?
A: Any pattern involving control flow, side effects, unpredictable values.

Q: Are `StringBuilder`-s flawless?
A: They are aggressively optimized, but sometimes even those optos fail.

Q: I am PL professional, give me lazy-val, call-by-name, and shut up.
A: *(points to JDK 8 release, and PL professional leaves enlightened)*

Hash Codes

Zeroes: P(31) hashcode

Spec says `String.hashCode` is a P(31) polynomial hashcode:

$$h(s) = \sum_{k=0}^{n-1} 31^{n-k-1} s_k$$

```
public int hashCode() {
  ...
  int h = 0;
  for (char v : value) {
    h = 31 * h + v;
  }
  hash = h;
}
```

Time complexity is $\Omega(N)$ and $O(N)$.

Zeroes: Trying...

```
String str1, str2;

@Setup
public void setup() {
  str1 = "лжеотождествление␣электровиолончели"; // same length
  str2 = "электровиолончели␣лжеотождествление"; // same length
}

@Benchmark
int test1() { return str1.hashCode(); }

@Benchmark
int test2() { return str2.hashCode(); }
```

Zeroes: Trying...

```
String str1, str2;

@Setup
public void setup() {
  str1 = "лжеотождествление␣электровиолончели"; // same length
  str2 = "электровиолончели␣лжеотождествление"; // same length
}

@Benchmark
int test1() { return str1.hashCode(); } // 22.663 ± 0.056 ns/op

@Benchmark
int test2() { return str2.hashCode(); } // 0.758 ± 0.002 ns/op
```

Zeroes: Actual Implementation

```
public int hashCode() {
  int h = hash;
  if (h == 0) {
    for (char v : value) {
      h = 31 * h + v;
    }
    hash = h;
  }
  return h;
}
```

- Actual code caches hashcodes
- Immense improvements in most scenarios, justifying 4 bytes per instance
- By *pigeonhole principle*, some Strings are bound to have $hs(s) = 0$, sucks to be them
- It is a sane engineering tradeoff to have a performance anomaly with 2^{-32} probability

Collisions: Walking on a Sunshine

```
// carefully populated with unicorn dust:
HashMap<String, String> sunshine;

@Benchmark void keySet(Blackhole bh) {
  for (String key : sunshine.keySet()) {
    bh.consume(sunshine.get(key));
  }
}

@Benchmark void entrySet(Blackhole bh) {
  for (Map.Entry<String, String> e : sunshine.entrySet()) {
    bh.consume(e);
  }
}
```

Collisions: Using JDK 7u0...

Benchmark	Size	Time, ns/op		ns/key
entrySet	1	14.134	± 0.028	14.1
entrySet	10	47.427	± 0.269	4.7
entrySet	100	294.148	± 0.934	2.9
entrySet	1000	5366.982	± 802.857	5.4
entrySet	10000	67394.472	± 456.576	6.7
keySet	1	18.463	± 0.500	18.4
keySet	10	279.816	± 6.783	27.8
keySet	100	22266.667	± 179.695	222.7
keySet	1000	2716486.481	± 10145.741	2716.5
keySet	10000	355309390.210	± 1214802.832	355309.4

keySet performance rapidly deteriorates: $O(N^2)$

Collisions: Algorithmic Attacks

Polynomial hash functions make artificial collisions a piece of cake.
Suppose this expansion:

$$h(s) = \sum_{k=0}^{n-1} 31^{n-k-1} s_k = [\sum_{k=0}^{n-3} 31^{n-k-1} s_k] + 31 s_{n-2} + s_{n-1}$$

Then, if strings a and b have common prefix in $[0..n-3]$:

$$h(a) = h(b) \Leftrightarrow 31(a_{n-2} - b_{n-2}) = (a_{n-1} - b_{n-1})$$

...and that is super-easy, suppose $a = $"$...Aa$" and $b = $"$...BB$".

Collisions: Why should I care?

- Alice is running her battle-hardened HTTP server, patched up for Heartbleed, Shellshock, all these fancy-named vulnerabilities.
  Alice is serious about security.
- Mallory giggles and sends the HTTP Request with these HTTP Headers:

```
"X-Conference-AaAaAaAa:␣JokerConf␣2014,␣Why␣So␣Serious?"
"X-Conference-AaAaAaBB:␣JokerConf␣2014,␣Why␣So␣Serious?"
"X-Conference-AaAaBBAa:␣JokerConf␣2014,␣Why␣So␣Serious?"
"X-Conference-AaAaBBBB:␣JokerConf␣2014,␣Why␣So␣Serious?"
```

- Alices's web server accepts the request, stores HTTP Headers in `Map<String, String>`, and then tries to process them. Boom, resource exhaustion and possible DoS.

Collisions: Using JDK 8

Benchmark	Size	Time, ns/op		ns/key
entrySet	1	11.674	± 0.040	11.7
entrySet	10	36.301	± 0.076	3.6
entrySet	100	278.057	± 0.726	2.8
entrySet	1000	3606.722	± 21.441	3.6
entrySet	10000	86459.477	± 626.407	8.6
keySet	1	15.050	± 0.084	15.0
keySet	10	253.241	± 0.650	2.5
keySet	100	10072.577	± 144.418	100.7
keySet	1000	158591.766	± 1202.430	158.6
keySet	10000	2355039.389	± 12087.352	235.3

keySet is now $O(NlogN)$ – not as bad

Collisions: Another quirks

`http://www.zlib.net/crc_v3.txt`

> *In particular, any CRC algorithm that initializes its register to zero will have a blind spot of zero when it starts up and will be unable to "count"a leading run of zero bytes. As a leading run of zero bytes is quite common in real messages, it is wise to initialize the algorithm register to a non-zero value.*

The same applies to `String.hashCode`.
Thank God, NUL-prefixed Strings are not common.

Hash Codes: Catechism

Q: Should I care about `String.hashCode`?
A: Most likely not, unless you expose your naked `Maps` for user input.

Q: Should I wrap the `Strings` with my own `hashCode` implementation?
A: In some very rare cases, yes.

Q: Why TIAO wouldn't change the `String.hashCode` computation?
A: The P(31) hashcode is spec-ed in so many places, it can't be changed now.

Q: That `hashCode` caching thing at zero bothers me, can be do a `boolean` flag?
A: That will explode `String` footprint by 8 bytes in worst case.

Substring

Substring: JDK 8

```
java.lang.String object internals:
 OFFSET  SIZE   TYPE DESCRIPTION
      0    12        (object header)
     12     4 char[] String.value
     16     4    int String.hash
     20     4        (alignment loss)
Instance size: 24 bytes
```

Seasoned Java devs can wonder...

Substring: JDK 8

```
java.lang.String object internals:
 OFFSET  SIZE   TYPE DESCRIPTION
      0    12        (object header)
     12     4 char[] String.value
     16     4    int String.hash
     20     4        (alignment loss)
Instance size: 24 bytes
```

Seasoned Java devs can wonder... where are `offset` and `count` fields?

Substring: JDK < 7u6

```
java.lang.String object internals:
 OFFSET  SIZE   TYPE DESCRIPTION
      0    12        (object header)
     12     4 char[] String.value
     16     4    int String.offset
     20     4    int String.count
     24     4    int String.hash
     28     4        (alignment loss)
Instance size: 32 bytes
```

Here they are! Left behind the enemy lines in JDK 7.

Substring: Benchmark

```
@Param({"0", "30", "60", "90", "120"})
int limit;

String str;

@Setup
public void setup() {
  str = "JokerConf␣2014:␣Why␣So␣Serious?␣" +
        "JokerConf␣2014:␣Why␣So␣Serious?␣" +
        "JokerConf␣2014:␣Why␣So␣Serious?␣" +
        "JokerConf␣2014:␣Why␣So␣Serious?␣";
}

@Benchmark
String head() { return str.substring(limit); }

@Benchmark
String tail() { return str.substring(0, limit); }
```

Substring: JDK $<$ 7u6: Sharing

Limit	Score, ns/op			
	head		tail	
0	2.278	± 0.007	3.763	± 1.091
30	3.566	± 0.261	3.626	± 0.787
60	3.524	± 0.159	3.466	± 0.188
90	3.763	± 0.431	3.464	± 0.089
120	3.713	± 1.053	3.446	± 0.141

- `substring()` only instantiates `Strings`, shares `char[]` arrays
- This is believed to cause memory leaks: think large XML and substring on it

Substring: JDK 8: Copying

Limit	Score, ns/op			
	head		tail	
0	2.277	± 0.012	19.401	± 0.317
30	22.976	± 0.074	10.066	± 0.049
60	16.875	± 0.071	15.202	± 0.116
90	12.782	± 0.088	21.720	± 0.574
120	11.086	± 0.354	26.602	± 0.123

- `substring()` now copies the entire `char[]` array
- Works reasonably well for small substrings, avoids memory leaks

Substring: Catechism

Q: New `substring` sounds bad, can I get it back?
A: No, you can't.

Q: But why?
A: Real memory leaks are worse than potential performance issues.

Q: What if I need $O(1)$ `substring`?
A: That means you care about this enough to make your own storage.

Q: But my application was using `substring` for performance reasons!
A: *(Points to a String.substring Javadoc, and Engineer leaves enlightened)*

Intern

Intern: Interning vs. Deduplication

Deduplication:
Reduce # of instances in each equivalence class

Interning (canonicalization):
Reduce # of instances in each equivalence class to one (canonical) instance.

- As usual, enforcing *stronger* property costs more
- In many cases, you want *deduplication*, not *interning*

Intern: User Interners

Interning is dead-simple, and can be done by hand:

```
public class CHMInterner<T> {
  private final Map<T, T> map;

  public CHMInterner() {
    map = new ConcurrentHashMap<>();
  }

  public T intern(T t) {
    T exist = map.putIfAbsent(t, t);
    return (exist == null) ? t : exist;
  }
}
```

Intern: User Interners (cont.)

Benchmark	Size	Time, us/op	
chm	100	2.448	± 0.014
chm	10000	242.994	± 0.944
chm	1000000	47537.076	± 2123.834
hm	100	0.929	± 0.008
hm	10000	133.796	± 0.748
hm	1000000	35349.188	± 1188.810
intern	100	8.011	± 0.277
intern	10000	891.871	± 13.602
intern	1000000	315664.776	± 17821.360

(Throw-away) `(Concurrent)HashMap` is order of magnitude better!

Intern: And the reason is:

`String.intern()` is a gateway to VM internal StringTable.
StringTable is fixed-size, and almost always overloaded:

```
-XX:+PrintStringTableStatistics
StringTable statistics:
Number of buckets       :      60013 =     480104 bytes, avg    8.000
Number of entries       :    1002451 =   24058824 bytes, avg   24.000
Number of literals      :    1002451 =   64168512 bytes, avg   64.012
Total footprint         :            =   88707440 bytes
Average bucket size     :     16.704
Variance of bucket size :      9.731
Std. dev. of bucket size:      3.119
Maximum bucket size     :         27
```

User-issued `String.intern()` calls only make it worse!

Intern: User Deduplicators

Relaxing the canonicalization requirement may bring the performance:

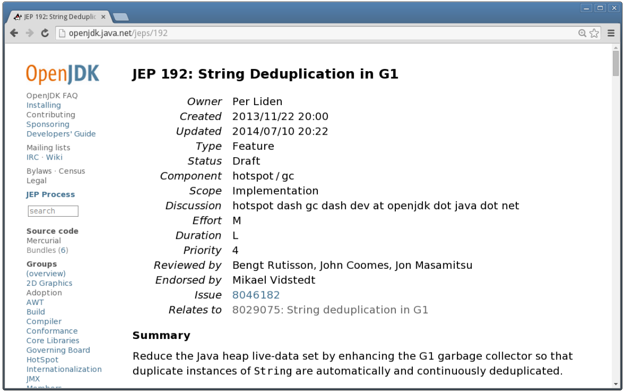
```java
public class CHMDeduplicator<T> {
  private final int prob;
  private final Map<T, T> map;

  public CHMDeduplicator(double prob) {
    this.prob = (int) (Integer.MIN_VALUE + prob * (1L << 32));
    this.map = new ConcurrentHashMap<>();
  }

  public T dedup(T t) {
    if (ThreadLocalRandom.current().nextInt() > prob) {
      return t;
    }
    T exist = map.putIfAbsent(t, t);
    return (exist == null) ? t : exist;
  }
}
```

Intern: Probabilistic Deduplicators

	time, us/op					
Prob	chm		hm		intern	
0.0	3.291	± 0.039	3.286	± 0.030	3.336	± 0.084
0.1	6.953	± 0.039	7.289	± 0.760	13.165	± 0.109
0.2	10.437	± 0.348	9.723	± 0.669	22.493	± 0.127
0.3	13.416	± 0.156	12.027	± 0.146	31.983	± 0.257
0.4	16.457	± 0.098	14.162	± 0.081	40.367	± 0.292
0.5	19.146	± 0.123	15.926	± 0.141	49.379	± 0.806
0.6	21.727	± 1.049	16.693	± 0.285	56.614	± 0.595
0.7	22.465	± 0.154	15.996	± 0.135	63.389	± 1.061
0.8	23.712	± 0.568	15.414	± 0.092	70.731	± 2.515
0.9	25.775	± 0.961	13.986	± 0.121	76.481	± 0.770
1.0	26.140	± 0.089	11.582	± 0.046	118.165	± 30.009

Intern: GC Deduplication

Why can't JVM do this for us?



JEP 192: String Deduplication in G1

Owner	Per Liden
Created	2013/11/22 20:00
Updated	2014/07/10 20:22
Type	Feature
Status	Draft
Component	hotspot / gc
Scope	Implementation
Discussion	hotspot dash gc dash dev at openjdk dot java dot net
Effort	M
Duration	L
Priority	4
Reviewed by	Bengt Rutisson, John Coomes, Jon Masamitsu
Endorsed by	Mikael Vidstedt
Issue	8046182
Relates to	8029075: String deduplication in G1

Summary

Reduce the Java heap live-data set by enhancing the G1 garbage collector so that duplicate instances of `String` are automatically and continuously deduplicated.

```
-XX:+UseG1GC -XX:+UseStringDeduplication
```

Intern: GC Deduplication

```
public static void main(String... args) {
  List<String> strs = ...;

  String last = GraphLayout.parseInstance(strs).toFootprint();
  System.out.println("***␣Original:␣" + last);

  for (int gc = 0; gc < 100; gc++) {
    String cur = GraphLayout.parseInstance(strs).toFootprint();

    if (!cur.equals(last)) {
      System.out.println("***␣GC␣changed:␣" + cur);
      last = cur;
    }

    System.gc();
  }
}
```

Use JOL[4] to estimate the memory footprint.

[4] http://openjdk.java.net/projects/code-tools/jol/

Intern: GC Deduplication

```
*** Original:
java.util.ArrayList instance footprint:
     COUNT       AVG       SUM   DESCRIPTION
     10000        47    472000   [C
         1     56232     56232   [Ljava.lang.Object;
     10000        24    240000   java.lang.String
         1        24        24   java.util.ArrayList
     20002              768256   (total)

*** GC changed:
java.util.ArrayList instance footprint:
     COUNT       AVG       SUM   DESCRIPTION
       100        47      4720   [C
         1     56232     56232   [Ljava.lang.Object;
     10000        24    240000   java.lang.String
         1        24        24   java.util.ArrayList
     10102              300976   (total)
```

Notice the `char[]` arrays are de-duplicated.

Intern: GC Deduplication

```
*** GC changed:
java.util.ArrayList instance footprint:
     COUNT          AVG         SUM   DESCRIPTION
       100           47        4720   [C
         1        56232       56232   [Ljava.lang.Object;
     10000           24      240000   java.lang.String
         1           24          24   java.util.ArrayList
     10102                   300976   (total)

*** Dedup:
java.util.ArrayList instance footprint:
     COUNT          AVG         SUM   DESCRIPTION
       100           47        4720   [C
         1        56232       56232   [Ljava.lang.Object;
       100           24        2400   java.lang.String
         1           24          24   java.util.ArrayList
       202                    63376   (total)
```

Hand-rolled deduplicator can also reduce the number of `String`-s.

Intern: Catechism

Q: But I read so much on using `String.intern` for improving footprint.
A: `http://en.wikipedia.org/wiki/Hanlon's_razor`

Q: I will use `String.intern` just on this tiny little location.
A: Excellent, you already know where your bottlenecks are going to be.

Q: Why wouldn't TIAO optimize `String.intern`?
A: We **are** improving it. It does not help the *misuse* of `String.intern`.

Q: Should I rely on GC deduplication for ultimate memory savings?
A: Identity rules disallow us to merge objects, you have to merge them yourself.

Equals

Equals: Testing basic things

```
String bar10_0 = "BarBarBarA", bar10_1 = "BarBarBarA";
String bar10_2 = "BarBarBarB", bar10_3 = "ABarBarBar";
String bar11   = "BarBarBarAB";

@Benchmark
boolean sameChar()          { return bar10_0.equals(bar10_1); }

@Benchmark
boolean sameLen_diffEnd()   { return bar10_0.equals(bar10_2); }

@Benchmark
boolean sameLen_diffStart() { return bar10_0.equals(bar10_3); }

@Benchmark
boolean differentLen()      { return bar10_0.equals(bar11); }
```

Equals: Basic characteristics

Benchmark	Score, ns/op	
sameChar	0.994	± 0.044
differentLen	1.316	± 0.007
sameLen_diffEnd	4.556	± 0.014
sameLen_diffStart	2.565	± 0.010

- Strings instantiated off the same constant are interned, == check is fast
- Strings of different lengths are not compared at all
- Strings are matched from start to end

Equals: Implementation

```
public boolean equals(Object anObject) {
  if (this == anObject) {
    return true;
  }
  if (anObject instanceof String) {
    String anotherString = (String)anObject;
    int n = value.length;
    if (n == anotherString.value.length) {
      char v1[] = value;
      char v2[] = anotherString.value;
      int i = 0;
      while (n-- != 0) {
        if (v1[i] != v2[i])
          return false;
         i++;
      }
      return true;
    }
  }
  return false;
}
```

«I think this version is well-optimized, and you can gain nothing here...»
(somebody on StackOverflow)

Equals: Intrinsics

Benchmark	Score, ns/op			
	default		disabled[5]	
sameChar	0.994	± 0.044	1.011	± 0.003
differentLen	1.316	± 0.007	1.325	± 0.015
sameLen_diffEnd	4.556	± 0.014	9.654	± 0.052
sameLen_diffStart	2.565	± 0.010	2.989	± 0.050

- The actual `equals()` implementation is intrinsified
- Blindly rewriting the Java implementation will not be faster
- How can intrinsified implementation be 2x faster than «optimal» Java code?

[5] `-XX:+UnlockDiagnosticVMOptions -XX:DisableIntrinsic=::_equals`

Equals: Intrinsics (cont.)

Intrinsic version is vectorized:

```
  5.23%     3.42%    0x00007f1b8c93de95: mov    (%rdi,%rcx,1),%ebx
 14.73%     4.01%    0x00007f1b8c93de98: cmp    (%rsi,%rcx,1),%ebx
                     0x00007f1b8c93de9b: jne    0x00007f1b8c93debb
 26.39%    27.41%    0x00007f1b8c93de9d: add    $0x4,%rcx
                     0x00007f1b8c93dea1: jne    0x00007f1b8c93de95
```

- Notice comparing in 4-byte strides
- This works regardless of whether compiler can or can't auto-vectorize
- VM will select SSE, AVX, etc to efficiently compare.

Equals: Catechism

Q: I have this very nifty idea of optimizing `String.equals`...
A: If you are not prepared to deal with low-level assembly, do not even start.

Q: Why would you need a Java version for `String.equals` then?
A: Interpreter, C1, and other compilers still use this as the fallback code.

Q: Should I intern the `Strings` and then == on them instead?
A: It would be easier to just check the `hashCode` before.

Q: But interning is so much easier!
A: *(silence is the answer, and Programmer leaves enlightened)*

Regexps

Regexps: splitting

```
String text = "Глокая␣куздра␣штеко␣будланула␣бокра␣и␣курдячит␣бокрёнка
String textDup = text.replaceAll("␣", "␣␣");
Pattern pattern = Pattern.compile("␣␣");

@Benchmark
String[] charSplit()          { return text.split("␣"); }

@Benchmark
String[] strSplit()           { return textDup.split("␣␣"); }

@Benchmark
String[] strSplit_pattern() { return pattern.split(textDup); }
```

Regexps: Splitting

Benchmark	Time, ns/op	
charSplit	191.657	± 1.798
strSplit	527.952	± 5.578
strSplit_pattern	416.219	± 4.075

- charSplit has a fast-path for a single-char patterns
- strSplit uses Pattern to match: do not be suprised it works much slower
- strSplit_pattern reuses the Pattern: saves a few cycles

Regexps: Other methods

Lots of other `String` methods are using `Pattern` implicitly:

- `matches(String regex)`
- `replaceFirst(String regex, String replacement)`
- `replaceAll(String regex, String replacement)`
- `replace(CharSequence target, CharSequence replacement)`
- `split(String regex)`
- `split(String regex, int limit)`

You may want to cache `Pattern` in performance-critical places.

Regexps: Backtracking

Searching with `Pattern.compile("(x+x+)+y")`:

Text	Time, ns/op		
size	"xx...xxy"		"xx..xx"
4	94.520	± 1.270	
6	96.848	± 0.936	
8	102.765	± 1.568	
10	106.553	± 5.027	
12	106.786	± 1.515	
14	111.983	± 1.573	
16	115.642	± 2.114	

Regexps: Backtracking

Searching with `Pattern.compile("(x+x+)+y")`:

Text	Time, ns/op			
size	"xx...xxy"		"xx..xx"	
4	94.520	± 1.270	291.830	± 9.274
6	96.848	± 0.936	1049.571	± 7.291
8	102.765	± 1.568	4028.029	± 49.917
10	106.553	± 5.027	15900.084	± 263.320
12	106.786	± 1.515	61694.528	± 704.420
14	111.983	± 1.573	245397.200	± 1528.407
16	115.642	± 2.114	989130.322	± 11201.690

Given the mismatching text, the regexp catastrophically backtracks.

Regexps: Catechism

Q: Should I care? I would never use regular expressions.
A: Yes, you will. Learn how to deal with them before it's too late.

Q: Okay, what are the major improvements I can do?
A: Simplify and cache `Pattern`-s.

Q: Catastrophic backtracking sounds very theoretical, do I have to care?
A: Yes. Unsanitized texts and/or unsanitized regexps are the way to DoS.

Q: Stand back! I know Regular Expressions!
A: *(stands back, and Engineer smacks into wall achieving enlightenment.)*

Walking

Walking: charAt vs toCharArray

```
@Benchmark
public int charAt() {
  int r = 0;
  for (int c = 0; c < text.length(); c++) {
    r += text.charAt(c);
  }
  return r;
}

@Benchmark
public int toCharArray() {
  int r = 0;
  char[] chars = text.toCharArray();
  for (int c = 0; c < text.length(); c++) {
    r += chars[c];
  }
  return r;
}
```

Walking: charAt vs toCharArray

Benchmark	Size	Time, ns/op
charAt	1	2.152 ± 0.002
charAt	10	4.794 ± 0.001
charAt	100	51.579 ± 0.016
charAt	1000	734.582 ± 0.335
toCharArray	1	6.502 ± 0.034
toCharArray	10	9.951 ± 0.050
toCharArray	100	61.204 ± 1.179
toCharArray	1000	1242.236 ± 4.591

- `charAt` bound-checks, but those are nicely optimized out
- `toCharArray` pays for spare memory allocation

Walking: charAt vs toCharArray (spoiled)

```
@Benchmark
public int charAt_spoil() {
  int r = 0;
  for (int c = 0; c < text.length(); c++) {
    spoiler(); // empty non-inlineable
    r += text.charAt(c);
  }
  return r;
}

@Benchmark
public int toCharArray_spoil() {
  int r = 0;
  char[] chars = text.toCharArray();
  for (char c : chars) {
    spoiler(); // empty non-inlineable
    r += c;
  }
  return r;
}
```

Walking: charAt vs toCharArray (spoiled)

Benchmark	size	Score, ns/op	
charAt_spoil	1	4.750	± 1.073
charAt_spoil	10	32.306	± 0.019
charAt_spoil	100	607.965	± 0.206
charAt_spoil	1000	10247.538	± 1552.360
toCharArray_spoil	1	8.903	± 0.042
toCharArray_spoil	10	28.550	± 0.100
toCharArray_spoil	100	435.444	± 3.398
toCharArray_spoil	1000	6559.925	± 22.723

- When VM is unable to track `text`, devirt and bounds-check elimination fail
- Local array is perfectly fine

Walking: Catechism

Q: Should I copy out the `char[]` array or not?
A: If you don't need performance, both approaches are the question of style.

Q: I care about performance, should I copy out the `char[]` array?
A: You should, in non-trivial case.

Q: What is considered non-trivial case?
A: Non-local control flow, volatile reads, etc. that break commonning.

Q: This sucks. There is no universal best-performance way?
A: *(silence was the answer, and Engineer left enligthened)*

Search

Search: Character searches

Searching in `"abcdefghiklmnopqrstuvxyz"`:

image	Time, ns/op			
	indexOf		lastIndexOf	
a	1.306	± 0.001	8.557	± 0.036
m	4.879	± 0.002	5.738	± 0.006
z	7.360	± 0.010	1.677	± 0.000

- Both `indexOf` and `lastIndexOf` are $O(n)$, obviously
- Either is more performant if searched from the start or the end

Search: Intrinsics

Benchmark	Image	Score, ns/op			
		+Opt		-Opt[6]	
indexOf	abc	5.036	± 0.002	4.912	± 0.080
indexOf	mno	7.049	± 0.004	9.875	± 0.076
indexOf	xyz	11.595	± 0.004	12.790	± 0.071
lastIndexOf	abc	13.977	± 0.034	13.956	± 0.031
lastIndexOf	mno	10.588	± 0.003	10.588	± 0.004
lastIndexOf	xyz	5.369	± 0.002	5.370	± 0.002

- Real implementation of `indexOf` is intrinsified
- Uses SSE/AVX extensions to search for a match

[6] `-XX:+UnlockDiagnosticVMOptions -XX:DisableIntrinsic=::_indexOf`

Search: Genome Search

Searching for a sequence of codons in Human Y chromosome:

Benchmark	Time, ms/op	
indexOf	48.262	± 0.434
wikipediaBM	16.741	± 0.497

- `str.indexOf(im)` is a naive search
- `wikipediaBM` is the copy-paste from Boyer-Moore wiki page[7]

[7] `http://en.wikipedia.org/wiki/Boyer-Moore_string_search_algorithm`

Search: Genome Search

Searching for a sequence of codons in Human Y chromosome:

Benchmark	Time, ms/op	
indexOf	48.262	± 0.434
wikipediaBM	16.741	± 0.497
matcherFind	21.223	± 0.429

- `str.indexOf(im)` is a naive search
- `wikipediaBM` is the copy-paste from Boyer-Moore wiki page[7]
- `pattern(im).matcher(str).find()` also uses BM

[7] http://en.wikipedia.org/wiki/Boyer-Moore_string_search_algorithm

Search: Catechism

Q: Why there is no optimal string search algo in JDK?
A: «Optimal» is in the eye of beholder.

Q: Why would you maintain a trivial `String.indexOf` anyway?
A: Small images are working better with trivial search.

Q: Java sucks for <insert domain here> because of `indexOf`.
A: *(points to 3rd party libraries, and Engineer leaves enlightened)*

Conclusion

Conclusion: ...

- `String`s are well-optimized:
  - Learning what optimizations are there, and how you can employ them is a useful skill
  - Learning what JDK/VM does is a useful skill
- Performance advice has a generally low «shelf life»:
  - Re-learn stuff as you go
  - Do not trust folklore