Effective Software

Lecture 7: Virtual machine, JVM bytecode, (de-)compilers, disassembler, profiling

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[1] Oaks, S.: Java Performance: 2nd Edition. O'Reilly, USA 2020.
[2] Fog, A.: The microarchitecture of Intel, AMD and VIA CPU, 2016.
[3] JVM source code - http://openjdk.java.net

Outline

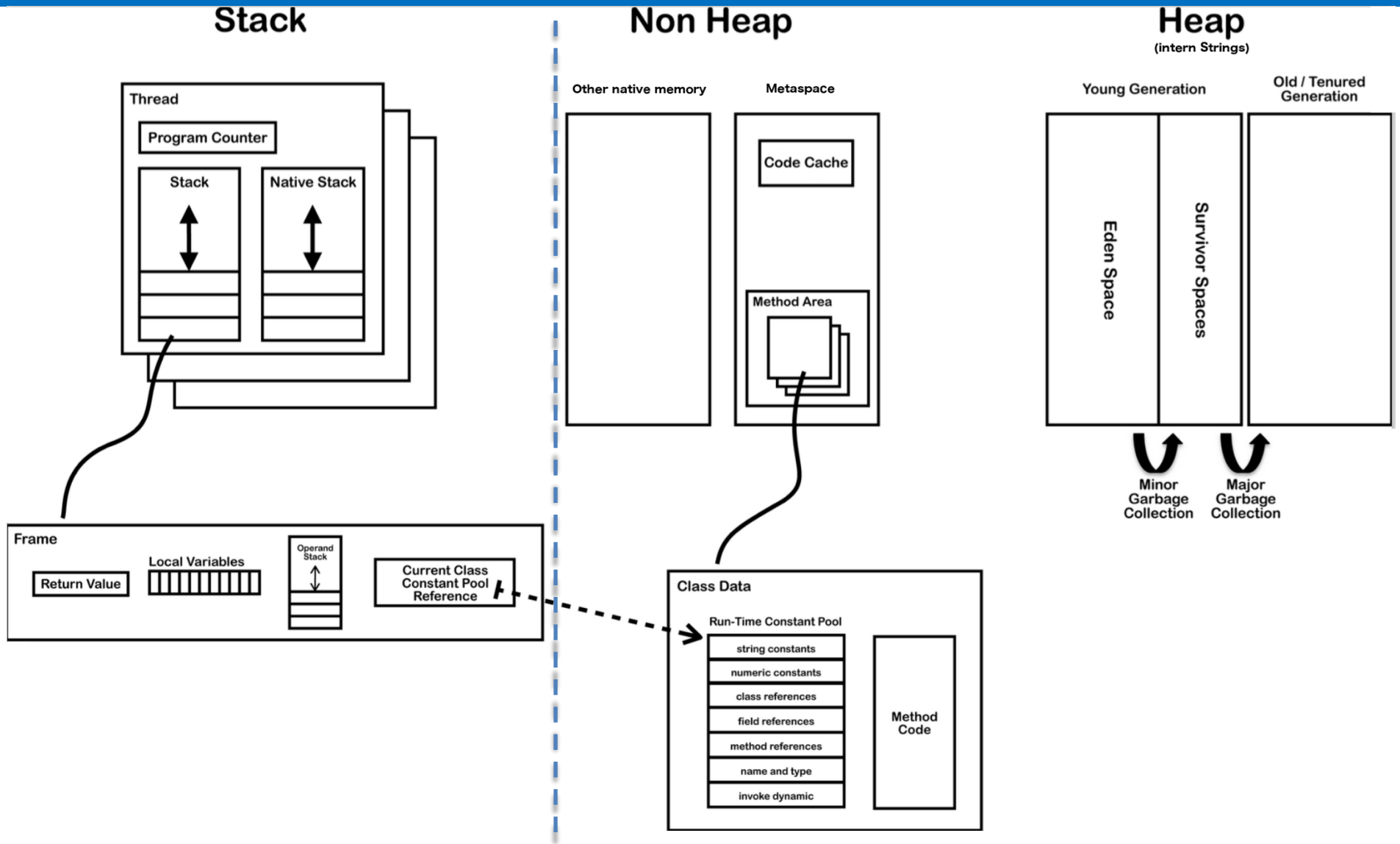
- Introduction to Virtual Machine
- Memory layout
  - Stack, Frames
- JVM bytecode
  - Disassembler
  - Decompiler
- Just-in-time compilation
  - Tiered approach
  - Optimizations
  - Assembly code analysis
- Safepoint
- Application profiling
  - Sampling
  - Tracing

Introduction – Virtual Machine

» **Virtual machine** model (NET, JVM – Scala, Kotlin, Jython, JRuby, Clojure, …)
- source code
- compiled into VM *bytecode*
- hybrid run-time environment (platform dependent VM implementation)
  - interpreted *bytecode*
  - *complied assembly-code* (native CPU code)
  - automated platform capability optimizations (e.g. use of SIMD)

» comparison of **bytecode** to **assembly-code**
- (+) platform independence (portable) – architecture (RISC/CISC, bits), OS
- (+) reflection – observe, modify own structure at run-time
- (+) small size
- (-) slower execution – interpreted mode, compilation latencies
- (-) less control on assembly code – less options for custom optimization

JAVA Virtual Machine – Memory Layout



Thread specific

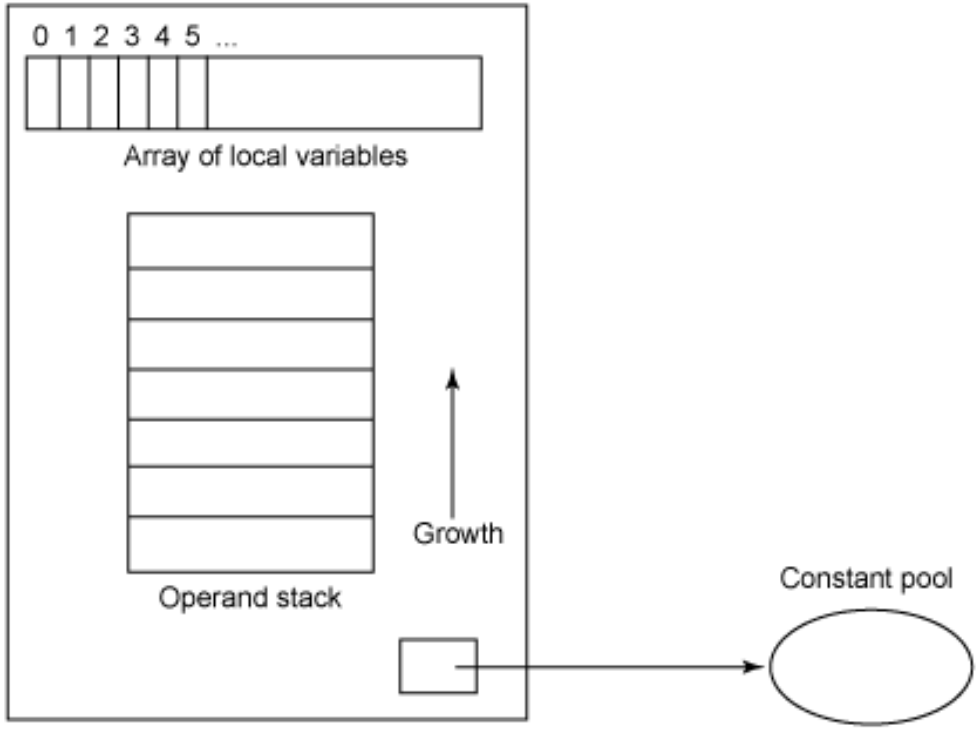
Shared by many threads

JAVA Virtual Machine - Frame

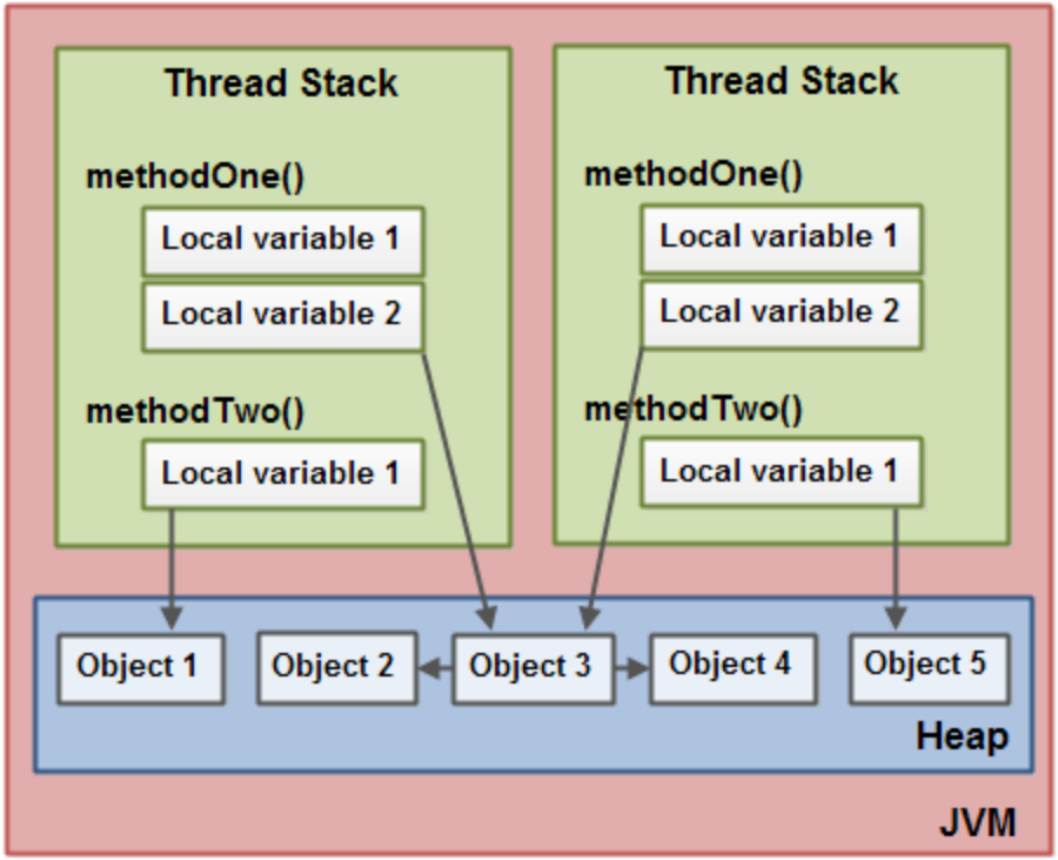
- **frame**
  - each thread has stack with frames (outside of heap, fixed length)

    StackOverflowError vs. OutOfMemoryError
  - frame is **created** each time method is invoked (**destroyed** after return)
    - ***interpreted frame*** per exactly one method
    - ***complied frame*** includes all in-lined methods
  - frame **size** determined at source compile-time (in class file for interpreted)
  - **variables** (any type)
    - {this} – *instance call only!*
    - {method arguments}
    - {local variables}
  - **operand stack** (any type)
    - LIFO
  - **reference to run-time**

    constant pool (class def)
  - method + class is associated



JAVA Virtual Machine – Memory Layout



» References in JVM are called Ordinary Object Pointers (OOP)

- **compressed** – 32 bit – able to address 32GB heap (using object alignment)
- **regular** – 64 bit

JAVA Virtual Machine – Stack-oriented Machine

» **JVM bytecode** uses **stack-oriented** approach for most operations

» **stack-oriented** - stack machine model for passing parameters and output for instructions

$$(2 + 3) \times 11 + 1$$

timeline →

Input	2	3	add	11	mul	1	add
Stack	2	3 2	5	11 5	55	1 55	56

» **JVM bytecode** – sequence of ***instructions*** composed of

- *opcode* – operation code, what should be done
- opcode specific *parameters* – some has no params, some multiple

JAVA Virtual Machine – Opcodes

- **JVM opcode** (1 Byte only always):
  - load and store (aload_0, istore, aconst_null, …)
  - arithmetic and logic (ladd, fcmpl, …)
  - type conversion (i2b, d2i, …)
  - object manipulation (new, putfield, getfield, …)
  - stack management (swap, dup2, …)
  - control transfer (ifeq, goto, …)
  - method invocation (invokespecial, areturn, …) – frame manipulation
  - exceptions and monitor concurrency (athrow, monitorenter, …)
- prefix/suffix – i, l, s, b, c, f, d and a (reference)
- variables as registers – e.g. istore_1 (variable 0 is **this** for instance method)

```
mov     %rax,%r8
shl     $0x5,%eax
sub     %r8d,%eax
add     %ecx,%eax
inc     %edx
```

CPU assembly-code
AT&T syntax

VS.

```
iconst_0
istore_3
iload_3
bipush        100
```

JVM bytecode

JAVA Virtual Machine – Object Oriented Language

» **Class file** – product of source code compilation
  - one per each class
  - method bytecode is included

```
ClassFile {
    u4              magic;
    u2              minor_version;
    u2              major_version;
    u2              constant_pool_count;
    cp_info         contant_pool[constant_pool_count - 1];
    u2              access_flags;
    u2              this_class;
    u2              super_class;
    u2              interfaces_count;
    u2              interfaces[interfaces_count];
    u2              fields_count;
    field_info      fields[fields_count];
    u2              methods_count;
    method_info     methods[methods_count];
    u2              attributes_count;
    attribute_info  attributes[attributes_count];
}
```

JAVA Virtual Machine – Example 1 – Source Code

```
public class Employee<Type> {
    private Type data;
    public int id;

    public Employee(Type data, int id) {
        update(data,id);
    }

    private void update(Type data, int id) {
        this.data = data;
        this.id = id;
    }

    public Type employeeData() {
        return data;
    }
}
```

notice usage of Generics

JAVA Virtual Machine – Example 1 – Class File Content

```
00000000  ca fe ba be 00 00 00 34  00 20 0a 00 06 00 19 0a  |.......4. ......|
00000010  00 05 00 1a 09 00 05 00  1b 09 00 05 00 1c 07 00  |................|
00000020  1d 07 00 1e 01 00 04 64  61 74 61 01 00 12 4c 6a  |.......data...Lj|
00000030  61 76 61 2f 6c 61 6e 67  2f 4f 62 6a 65 63 74 3b  |ava/lang/Object;|
00000040  01 00 09 53 69 67 6e 61  74 75 72 65 01 00 06 54  |...Signature...T|
00000050  54 79 70 65 3b 01 00 02  69 64 01 00 01 49 01 00  |Type;...id...I..|
00000060  06 3c 69 6e 69 74 3e 01  00 16 28 4c 6a 61 76 61  |.<init>...(Ljava|
00000070  2f 6c 61 6e 67 2f 4f 62  6a 65 63 74 3b 49 29 56  |/lang/Object;I)V|
00000080  01 00 04 43 6f 64 65 01  00 0f 4c 69 6e 65 4e 75  |...Code...LineNu|
00000090  6d 62 65 72 54 61 62 6c  65 01 00 0a 28 54 54 79  |mberTable...(TTy|
000000a0  70 65 3b 49 29 56 01 00  06 75 70 64 61 74 65 01  |pe;I)V...update.|
000000b0  00 0c 65 6d 70 6c 6f 79  65 65 44 61 74 61 01 00  |..employeeData..|
000000c0  14 28 29 4c 6a 61 76 61  2f 6c 61 6e 67 2f 4f 62  |.()Ljava/lang/Ob|
000000d0  6a 65 63 74 3b 01 00 08  28 29 54 54 79 70 65 3b  |ject;...()TType;|
000000e0  01 00 2b 3c 54 79 70 65  3a 4c 6a 61 76 61 2f 6c  |..+<Type:Ljava/l|
000000f0  61 6e 67 2f 4f 62 6a 65  63 74 3b 3e 4c 6a 61 76  |ang/Object;>Ljav|
00000100  61 2f 6c 61 6e 67 2f 4f  62 6a 65 63 74 3b 01 00  |a/lang/Object;..|
00000110  0a 53 6f 75 72 63 65 46  69 6c 65 01 00 0d 45 6d  |.SourceFile...Em|
00000120  70 6c 6f 79 65 65 2e 6a  61 76 61 0c 00 0d 00 1f  |ployee.java.....|
00000130  0c 00 12 00 0e 0c 00 07  00 08 0c 00 0b 00 0c 01  |................|
00000140  00 11 65 6d 70 6c 6f 79  65 65 2f 45 6d 70 6c 6f  |..employee/Emplo|
00000150  79 65 65 01 00 10 6a 61  76 61 2f 6c 61 6e 67 2f  |yee...java/lang/|
00000160  4f 62 6a 65 63 74 01 00  03 28 29 56 00 21 00 05  |Object...()V.!..|
00000170  00 06 00 00 00 02 00 02  00 07 00 08 00 01 00 09  |................|
00000180  00 00 00 02 00 0a 00 01  00 0b 00 0c 00 00 00 03  |................|
00000190  00 01 00 0d 00 0e 00 02  00 0f 00 00 00 2b 00 03  |.............+..|
000001a0  00 03 00 00 00 0b 2a b7  00 01 2a 2b 1c b7 00 02  |......*...*+....|
000001b0  b1 00 00 00 01 00 10 00  00 00 0e 00 03 00 00 00  |................|
000001c0  07 00 04 00 08 00 0a 00  09 00 09 00 00 00 02 00  |................|
000001d0  11 00 02 00 12 00 0e 00  02 00 0f 00 00 00 2b 00  |..............+.|
000001e0  02 00 03 00 00 00 0b 2a  2b b5 00 03 2a 1c b5 00  |.......*+...*...|
000001f0  04 b1 00 00 00 01 00 10  00 00 00 0e 00 03 00 00  |................|
00000200  00 0c 00 05 00 0d 00 0a  00 0e 00 09 00 00 00 02  |................|
00000210  00 11 00 01 00 13 00 14  00 02 00 0f 00 00 00 1d  |................|
00000220  00 01 00 01 00 00 00 05  2a b4 00 03 b0 00 00 00  |........*.......|
00000230  01 00 10 00 00 00 06 00  01 00 00 00 11 00 09 00  |................|
00000240  00 00 02 00 15 00 02 00  09 00 00 00 02 00 16 00  |................|
00000250  17 00 00 00 02 00 18                              |.......|
```

class constant pool

JAVA Virtual Machine – Example 1 – Disassembled Constants

» **javap** – JAVA **disassembler** included in JDK (readable form of class file)

```
public class employee.Employee<Type extends java.lang.Object> extends java.lang.Object
  minor version: 0
  major version: 52
  flags: ACC_PUBLIC, ACC_SUPER
Constant pool:
   #1 = Methodref          #6.#25         // java/lang/Object."<init>":()V
   #2 = Methodref          #5.#26         // employee/Employee.update:(Ljava/lang/Object;I)V
   #3 = Fieldref           #5.#27         // employee/Employee.data:Ljava/lang/Object;
   #4 = Fieldref           #5.#28         // employee/Employee.id:I
   #5 = Class              #29            // employee/Employee
   #6 = Class              #30            // java/lang/Object
   #7 = Utf8               data
   #8 = Utf8               Ljava/lang/Object;
   #9 = Utf8               Signature
  #10 = Utf8               TType;
  #11 = Utf8               id
  #12 = Utf8               I
  #13 = Utf8               <init>
  #14 = Utf8               (Ljava/lang/Object;I)V
  #15 = Utf8               Code
  #16 = Utf8               LineNumberTable
  #17 = Utf8               (TType;I)V
  #18 = Utf8               update
  #19 = Utf8               employeeData
  #20 = Utf8               ()Ljava/lang/Object;
  #21 = Utf8               ()TType;
  #22 = Utf8               <Type:Ljava/lang/Object;>Ljava/lang/Object;
  #23 = Utf8               SourceFile
  #24 = Utf8               Employee.java
  #25 = NameAndType        #13:#31        // "<init>":()V
  #26 = NameAndType        #18:#14        // update:(Ljava/lang/Object;I)V
  #27 = NameAndType        #7:#8          // data:Ljava/lang/Object;
  #28 = NameAndType        #11:#12        // id:I
  #29 = Utf8               employee/Employee
  #30 = Utf8               java/lang/Object
  #31 = Utf8               ()V
{
}
Signature: #22                          // <Type:Ljava/lang/Object;>Ljava/lang/Object;
```

Generics used only for compilation

JAVA Virtual Machine – Example 1 – Disassembled Fields

```
{
  private Type data;
    descriptor: Ljava/lang/Object;
    flags: ACC_PRIVATE
    Signature: #10                          // TType;

  public int id;
    descriptor: I
    flags: ACC_PUBLIC
```

- **descriptor** is used by VM – no generics included
- **signature** is used for compilation – contains Generics

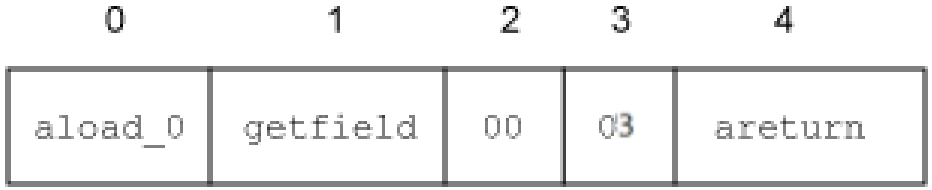
JAVA Virtual Machine – Example 1 – Disassembled Method

```
public Type employeeData();
  descriptor: ()Ljava/lang/Object;
  flags: ACC_PUBLIC
  Code:
    stack=1, locals=1, args_size=1
       0: aload_0
       1: getfield      #3                  // Field data:Ljava/lang/Object;
       4: areturn
    LineNumberTable:
      line 17: 0
  Signature: #21                           // ()TType;
```

```
16      public Type employeeData() {
17          return data;
18      }
```

opcode offset in bytecode
for the method employeeData

- » getfield
  - takes 1 ref from stack
  - build an index into runtime pool of class instance by reference **this**
- » areturn
  - takes 1 ref from stack
  - push onto the stack of calling method



JAVA Virtual Machine – Example 1 – Disassembled Constructor

```
public employee.Employee(Type, int);
  descriptor: (Ljava/lang/Object;I)V
  flags: ACC_PUBLIC
  Code:
    stack=3, locals=3, args_size=3
       0: aload_0
       1: invokespecial #1                  // Method java/lang/Object."<init>":()V
       4: aload_0
       5: aload_1
       6: iload_2
       7: invokespecial #2                  // Method update:(Ljava/lang/Object;I)V
      10: return
    LineNumberTable:
      line 7: 0
      line 8: 4
      line 9: 10
  Signature: #17                          // (TType;I)V

private void update(Type, int);
  descriptor: (Ljava/lang/Object;I)V
  flags: ACC_PRIVATE
  Code:
    stack=2, locals=3, args_size=3
       0: aload_0
       1: aload_1
       2: putfield      #3                  // Field data:Ljava/lang/Object;
       5: aload_0
       6: iload_2
       7: putfield      #4                  // Field id:I
      10: return
    LineNumberTable:
      line 12: 0
      line 13: 5
      line 14: 10
  Signature: #17                          // (TType;I)V
```

```
 7      public Employee(Type data, int id) {
 8          update(data,id);
 9      }
10
11      private void update(Type data, int id) {
12          this.data = data;
13          this.id = id;
14      }
```

JAVA Virtual Machine – Example 1 – Decompiler

» **procyon** – open-source JAVA **decompiler** (bytecode -> source code)

```
//
// Decompiled by Procyon v0.5.30
//

package employee;

public class Employee<Type>
{
    private Type data;
    public int id;

    public Employee(final Type type, final int n) {
        this.update(type, n);
    }

    private void update(final Type data, final int id) {
        this.data = data;
        this.id = id;
    }

    public Type employeeData() {
        return this.data;
    }
}
```

De-compiled source code

```
public class Employee<Type> {
    private Type data;
    public int id;

    public Employee(Type data, int id) {
        update(data,id);
    }

    private void update(Type data, int id) {
        this.data = data;
        this.id = id;
    }

    public Type employeeData() {
        return data;
    }
}
```

Original source code

JAVA Virtual Machine – Example 2 – Source Code

```java
private static Integer daysInMonth(int month, int year)
{
    int retVal;
    switch (month)
    {
        case 1:
        case 3:
        case 5:
        case 7:
        case 8:
        case 10:
        case 12:
            retVal=31;
            break;
        case 2:
            retVal = (year % 4 == 0 && (year % 100 != 0 || year % 400 == 0)) ? 29 : 28;
            break;
        case 4:
        case 6:
        case 9:
        case 11:
            retVal = 30;
            break;
        default:
            throw new IllegalArgumentException("Unknown month: " + month);
    }
    return new Integer(retVal);
}

private static int compute() {
    int month = 4;
    int year = 2000;
    int o=0;
    for (int i=0; i<1_000_000; i++) {
        o+=daysInMonth(month, year);
    }
    return o;
}
```

JAVA Virtual Machine – Example 2 – daysInMonth Bytecode

```
private static java.lang.Integer daysInMonth(int, int);
  descriptor: (II)Ljava/lang/Integer;
  flags: ACC_PRIVATE, ACC_STATIC
  Code:
    stack=4, locals=3, args_size=2
       0: iload_0
       1: tableswitch   { // 1 to 12
                     1: 64
                     2: 70
                     3: 64
                     4: 102
                     5: 64
                     6: 102
                     7: 64
                     8: 64
                     9: 102
                    10: 64
                    11: 102
                    12: 64
               default: 108
          }
      64: bipush        31
      66: istore_2
      67: goto          135
      70: iload_1
      71: iconst_4
      72: irem
      73: ifne          96
      76: iload_1
      77: bipush        100
      79: irem
      80: ifne          91
      83: iload_1
      84: sipush        400
      87: irem
      88: ifne          96
      91: bipush        29
      93: goto          98
      96: bipush        28
      98: istore_2
      99: goto          135
     102: bipush        30
     104: istore_2
     105: goto          135
```

```
int retVal;
switch (month)
{
    case 1:
    case 3:
    case 5:
    case 7:
    case 8:
    case 10:
    case 12:
        retVal=31;
        break;
    case 2:
        retVal = (year % 4 == 0 &&
                  (year % 100 != 0 ||
                   year % 400 == 0)) ?
                 29 : 28;
        break;
    case 4:
    case 6:
    case 9:
    case 11:
        retVal = 30;
        break;
    default:
        throw new IllegalArgumentException(
                "Unknown month: " + month);
}
return new Integer(retVal);
```

continues on the next slide …

JAVA Virtual Machine – Example 2 – daysInMonth Bytecode

```
 108: new           #2
 111: dup
 112: new           #3
 115: dup
 116: invokespecial #4
 119: ldc           #5
 121: invokevirtual #6
 124: iload_0
 125: invokevirtual #7
 128: invokevirtual #8
 131: invokespecial #9
 134: athrow
 135: new           #10
 138: dup
 139: iload_2
 140: invokespecial #11
 143: areturn
LineNumberTable:
  line 7: 0
  line 16: 64
  line 17: 67
  line 19: 70
  line 20: 99
  line 25: 102
  line 26: 105
  line 28: 108
  line 30: 135
StackMapTable: number_of_entries = 8
  frame_type = 251 /* same_frame_extended */
    offset_delta = 64
  frame_type = 5 /* same */
  frame_type = 20 /* same */
  frame_type = 4 /* same */
  frame_type = 65 /* same_locals_1_stack_item */
    stack = [ int ]
  frame_type = 3 /* same */
  frame_type = 5 /* same */
  frame_type = 252 /* append */
    offset_delta = 26
    locals = [ int ]
```

```
// class java/lang/IllegalArgumentException

// class java/lang/StringBuilder

// Method java/lang/StringBuilder."<init>":()V
// String Unknown month:
// Method java/lang/StringBuilder.append:(Ljava/lang/String;)Ljava/lang/StringBuilder;

// Method java/lang/StringBuilder.append:(I)Ljava/lang/StringBuilder;
// Method java/lang/StringBuilder.toString:()Ljava/lang/String;
// Method java/lang/IllegalArgumentException."<init>":(Ljava/lang/String;)V

// class java/lang/Integer


// Method java/lang/Integer."<init>":(I)V
```

```
            default:
                throw new IllegalArgumentException(
                        "Unknown month: " + month);
        }
        return new Integer(retVal);
```

StackMapTable – define variable types in Frame (variables and stack) at every bytecode jump target position

- first stack map automatically determined from method descriptor
- others are differential updates

JAVA Virtual Machine – Example 2 – compute Bytecode

```
private static int compute();
  descriptor: ()I
  flags: ACC_PRIVATE, ACC_STATIC
  Code:
    stack=3, locals=4, args_size=0
       0: iconst_4
       1: istore_0
       2: sipush        2000
       5: istore_1
       6: iconst_0
       7: istore_2
       8: iconst_0
       9: istore_3
      10: iload_3
      11: ldc           #12                 // int 1000000
      13: if_icmpge     33
      16: iload_2
      17: iload_0
      18: iload_1
      19: invokestatic  #13                 // Method daysInMonth:(II)Ljava/lang/Integer;
      22: invokevirtual #14                 // Method java/lang/Integer.intValue:()I
      25: iadd
      26: istore_2
      27: iinc          3, 1
      30: goto          10
      33: iload_2
      34: ireturn
    LineNumberTable:
      line 34: 0
      line 35: 2
      line 36: 6
      line 37: 8
      line 38: 16
      line 37: 27
      line 40: 33
    StackMapTable: number_of_entries = 2
      frame_type = 255 /* full_frame */
        offset_delta = 10
        locals = [ int, int, int, int ]
        stack = []
      frame_type = 250 /* chop */
        offset_delta = 22
```

for cycle

```
private static int compute() {
    int month = 4;
    int year = 2000;
    int o=0;
    for (int i=0; i<1_000_000; i++) {
        o+=daysInMonth(month, year);
    }
    return o;
}
```

No optimization during source code compilation !

Interpreted code execution is as inefficient as your source code !!!

bytecode offset 10 is related to for cycle bytecode start where there are 4 ints as local variables and no stack

JAVA Virtual Machine – Source Code Compilation

- **source code compilation** (*source code* => *bytecode*)
  - *bytecode* is not better than your *source code*
    - invariants in loop are not removed
  - **no optimizations** like
    - loop unrolling
    - algebraic simplification
    - strength reduction

obfuscation = make code difficult to be understood by humans but with the same functionality

- optionally *bytecode* can be modified before execution by JVM
  - e.g. **ProGuard** – *obfuscator* including bytecode optimizations
    - shrinker – **compact code**, remove dead code
    - optimizer
      - modify access pattern (private, static, final)
      - **inline** bytecode
    - obfuscator – renaming, layout changes
    - preverifier – ensure class loading

Test yourself
- compute method is simplified
- faster interpretation
- better JIT output

JAVA Virtual Machine – Bytecode Compilation in run-time

- **Just-in-time** (JIT)
  - converts bytecode into assembly code in run-time
  - check OpenJDK sources for very detailed information

    http://openjdk.java.net
- JIT includes **adaptive optimization** (adaptive tiered compilation since version 7)
  - balance trade-off between JIT and interpreting instructions
  - monitors frequently executed parts "hot spots" **including data** on caller-callee relationship for virtual method invocation
  - triggers dynamic re-compilation based on current execution profile
  - inline expansion to remove context switching
  - optimize branches
  - can make risky assumption (e.g. skip code) ->
    - unwind to valid state
    - de-optimize previously JITed code even if code is already executed
- Ahead-of-Time Compilation (AOT) – remove warm-up phase (removed Java 17)
  - compile into assembly code prior to launching the virtual machine

JAVA Virtual Machine – JIT Compilation

- *Just-in-time (JIT) compilers* – asynchronous (multiple threads)
  - **C1 compiler** – much faster compilation than C2
    - simplified inlining, use CPU registers
    - window-based optimization over small set of instructions
    - intrinsic functions with vector operations **SIMD** (Math, arraycopy, …)
  - **C2 compiler** – high-end fully optimizing compiler
    - dead code elimination, loop unrolling, loop invariant hoisting, common sub-expression elimination, constant propagation
    - full inlining, full de-optimization (back to level 0)
    - escape analysis, null check elimination,
    - pattern-based loop vectorization and super word packing (**SIMD**)
- **JIT compilation tiers** – adaptive compilation levels in JVM

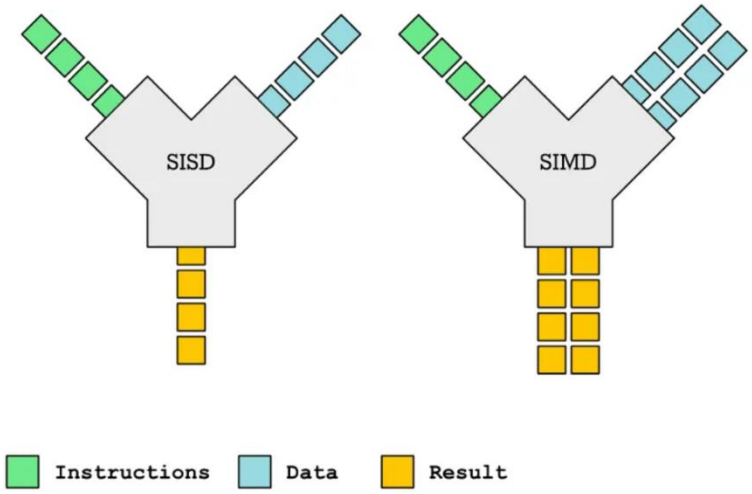
```
CompLevel_none                = 0,        // Interpreter
CompLevel_simple              = 1,        // C1
CompLevel_limited_profile     = 2,        // C1, invocation & backedge counters
CompLevel_full_profile        = 3,        // C1, invocation & backedge counters + mdo
CompLevel_full_optimization   = 4,        // C2
```

- **on-stack replacement** (OSR) – optimization during execution of a method
  - start at bytecode jump targets (goto, if_)

Assembly Code

» reasons to study **assembly code** (both Java and C/C++)

- educational reasons
  - predict efficient coding techniques
- debugging and verification
  - how well the code looks like
- optimize code
  1. **for speed**
     - avoid poorly compiled patterns
     - data fits into cache
     - predictable branches or no branches
     - use vector programing if possible (**SIMD**)
       - » 256bit registers with AVX2 since Intel Sandy Bridge
       - » 512bit AVX-512 since Intel Knight Landing (Xeon Phi)
     - new **Vector API** as incubator module since Java 16
  2. **for size**
     - primarily code cache efficiency



JAVA Virtual Machine – Example 2 – Tiered Compilation

» -XX:+PrintCompilation (-XX:+PrintInlining)

{millis from start} {compilation_task_id} {flags} {tier} {class:method} (bytecode size)@OSR {removing not rentrant/zombie}

```
   67    1       3       java.lang.String::hashCode (55 bytes)
   68    2       3       java.lang.String::charAt (29 bytes)
   69    3       3       java.lang.String::length (6 bytes)
   74    4       3       java.lang.String::indexOf (70 bytes)
   74    5     n 0       java.lang.System::arraycopy (native)   (static)
   74    6       3       java.lang.String::equals (81 bytes)
   75    8       3       java.lang.Object::<init> (1 bytes)
   75    9       3       java.lang.Math::min (11 bytes)
   75    7       3       java.lang.AbstractStringBuilder::ensureCapacityInternal (16 bytes)
   75   10       3       java.lang.AbstractStringBuilder::append (50 bytes)
   76   11       3       java.lang.String::getChars (62 bytes)
   81   12       1       java.lang.ref.Reference::get (5 bytes)
   81   13       3       java.lang.StringBuilder::append (8 bytes)
   82   14       3       java.lang.String::indexOf (7 bytes)
   83   16       3       java.lang.Number::<init> (5 bytes)
   83   19       1       java.lang.Object::<init> (1 bytes)
   84    8       3       java.lang.Object::<init> (1 bytes)   made not entrant
   84   18       3       SwitchTest::daysInMonth (144 bytes)
   84   17       3       java.lang.Integer::<init> (10 bytes)
   84   15       1       java.lang.Integer::intValue (5 bytes)
   84   20       4       SwitchTest::daysInMonth (144 bytes)
   86   18       3       SwitchTest::daysInMonth (144 bytes)   made not entrant
   88   21 %     3       SwitchTest::compute @ 10 (35 bytes)
   88   22       3       SwitchTest::compute (35 bytes)
   89   23 %     4       SwitchTest::compute @ 10 (35 bytes)
   91   21 %     3       SwitchTest::compute @ -2 (35 bytes)   made not entrant
   91   23 %     4       SwitchTest::compute @ -2 (35 bytes)   made not entrant
   92   24 %     4       SwitchTest::compute @ 10 (35 bytes)
   94   25       4       SwitchTest::compute (35 bytes)
   95   22       3       SwitchTest::compute (35 bytes)   made not entrant
```

Notice **standard compilation path 0 -> 3 -> 4**

JVM – Example 2 – daysInMonth Assembly Code – Tier 3

- -XX:+UnlockDiagnosticVMOptions -XX:+PrintAssembly
- **all examples are in JVM 8 64-bit, Intel Haswell CPU, AT&T syntax**

tier 3 - C1 with invocation & backedge counters + MethodDataOop (MDO) cnt.

because: count="256" iicount="256" **hot_count="256"**

stack initialization, **invocation counter** in MDO (0xDC) + **trigger** C2 (tier 4)

```
   127   17    b  3       SwitchTest::daysInMonth (144 bytes)
Decoding compiled method 0x0000000108a95190:
Code:
[Entry Point]
[Verified Entry Point]
[Constants]
  # {method} {0x000000012169d568} 'daysInMonth' '(II)Ljava/lang/Integer;' in 'SwitchTest'
  # parm0:    rsi       = int
  # parm1:    rdx       = int
  #           [sp+0x90]  (sp of caller)
  0x0000000108a95380: mov    %eax,-0x14000(%rsp)
  0x0000000108a95387: push   %rbp
  0x0000000108a95388: sub    $0x80,%rsp
  0x0000000108a9538f: mov    %rdx,%rdi
  0x0000000108a95392: movabs $0x12169db40,%rax  ;   {metadata(method data for {method} {0x000000012169d568} 'daysInMonth' '(II)Ljava/lang/Integer;' in 'SwitchTest')}
  0x0000000108a9539c: mov    0xdc(%rax),%edx
  0x0000000108a953a2: add    $0x8,%edx
  0x0000000108a953a5: mov    %edx,0xdc(%rax)
  0x0000000108a953ab: movabs $0x12169d568,%rax  ;   {metadata({method} {0x000000012169d568} 'daysInMonth' '(II)Ljava/lang/Integer;' in 'SwitchTest')}
  0x0000000108a953b5: and    $0x1ff8,%edx
  0x0000000108a953bb: cmp    $0x0,%edx
  0x0000000108a953be: je     0x0000000108a95996  ;*iload_0
                                                 ; - SwitchTest::daysInMonth@0 (line 7)
```

RSP – current stack position
R15 – current thread meta information
RAX – return value

month, year

stacking banging technique, StackOverflowException

stack frame allocation, saving registers

0x1ff8 >> 3 = 1024 invocations **trigger tier 4 (C2)**

continues on the next slide …

JVM – Example 2 – daysInMonth Assembly Code – Tier 3

```
0x0000000108a953c4: cmp    $0x1,%esi
0x0000000108a953c7: je     0x0000000108a95597
0x0000000108a953cd: cmp    $0x2,%esi
0x0000000108a953d0: je     0x0000000108a95435
0x0000000108a953d6: cmp    $0x3,%esi
0x0000000108a953d9: je     0x0000000108a95597
0x0000000108a953df: cmp    $0x4,%esi
0x0000000108a953e2: je     0x0000000108a9557d
0x0000000108a953e8: cmp    $0x5,%esi
0x0000000108a953eb: je     0x0000000108a95597
0x0000000108a953f1: cmp    $0x6,%esi
0x0000000108a953f4: je     0x0000000108a9557d
0x0000000108a953fa: cmp    $0x7,%esi
0x0000000108a953fd: je     0x0000000108a95597
0x0000000108a95403: cmp    $0x8,%esi
0x0000000108a95406: je     0x0000000108a95597
0x0000000108a9540c: cmp    $0x9,%esi
0x0000000108a9540f: je     0x0000000108a9557d
0x0000000108a95415: cmp    $0xa,%esi
0x0000000108a95418: je     0x0000000108a95597
0x0000000108a9541e: cmp    $0xb,%esi
0x0000000108a95421: je     0x0000000108a9557d
0x0000000108a95427: cmp    $0xc,%esi
0x0000000108a9542a: je     0x0000000108a95597
0x0000000108a95430: jmpq   0x0000000108a956d0  ;*tableswitch
                                               ; - SwitchTest::daysInMonth@1 (line 7)
```

ESI is month input

default jump

continues on the next slide …

JVM – Example 2 – daysInMonth Assembly Code – Tier 3

target for month=4, **backedge counter** tracking in MDO (0x290):

```
0x0000000108a9557d: movabs $0x12169db40,%rdx  ;   {metadata(method data for {method} {0x000000012169d568} 'daysInMonth' '(II)Ljava/lang/Integer;' in 'SwitchTest')}
0x0000000108a95587: incl   0x290(%rdx)
0x0000000108a9558d: mov    $0x1e,%ebx
0x0000000108a95592: jmpq   0x0000000108a955ac  ;*goto
                                               ; - SwitchTest::daysInMonth@105 (line 26)
```

EBX=30 is retVal

jump target, **inlined TLAB allocation** of Integer object:

```
0x0000000108a955ac: movabs $0x7c0011320,%rdx  ;   {metadata('java/lang/Integer')}
0x0000000108a955b6: mov    0x60(%r15),%rax
0x0000000108a955ba: lea    0x10(%rax),%rdi
0x0000000108a955be: cmp    0x70(%r15),%rdi
0x0000000108a955c2: ja     0x0000000108a959bc
0x0000000108a955c8: mov    %rdi,0x60(%r15)
0x0000000108a955cc: mov    0xa8(%rdx),%rcx
0x0000000108a955d3: mov    %rcx,(%rax)
0x0000000108a955d6: mov    %rdx,%rcx
0x0000000108a955d9: shr    $0x3,%rcx
0x0000000108a955dd: mov    %ecx,0x8(%rax)
0x0000000108a955e0: xor    %rcx,%rcx
0x0000000108a955e3: mov    %ecx,0xc(%rax)
0x0000000108a955e6: xor    %rcx,%rcx          ;*new  ; - SwitchTest::daysInMonth@135 (line 30)
```

0x10 **Integer** instance size

no space in **TLAB** -> new TLAB + external allocation with header init returns after the inlined allocation

object initialization, header filed with prototype mark

RAX Integer instance address

continues on the next slide …

Heap object structure (64-bit JVM):

- header 12 or 16 Bytes
- object data super class first, type grouped

8B - mark word
4B / 8B – Klass ref.
… object data

Heap 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

JVM – Example 2 – daysInMonth Assembly Code – Tier 3

inlined Integer constructor with supers, invocation counts in MDOs (0xDC)

Integer::<init>, Number::<init>, Object::<init>

- currently in tier 3 (C1 counters in MDO)

```
0x0000000108a955e9: mov    %rax,%rdx
0x0000000108a955ec: movabs $0x12169db40,%rsi  ;   {metadata(method data for {method} {0x000000012169d568} 'daysInMonth' '(II)Ljava/lang/Integer;' in 'SwitchTest')}
0x0000000108a955f6: addq   $0x1,0x358(%rsi)
0x0000000108a955fe: movabs $0x1214df850,%rdx  ;   {metadata(method data for {method} {0x0000000121341738} '<init>' '(I)V' in 'java/lang/Integer')}
0x0000000108a95608: mov    0xdc(%rdx),%esi
0x0000000108a9560e: add    $0x8,%esi
0x0000000108a95611: mov    %esi,0xdc(%rdx)
0x0000000108a95617: movabs $0x121341738,%rdx  ;   {metadata({method} {0x0000000121341738} '<init>' '(I)V' in 'java/lang/Integer')}
0x0000000108a95621: and    $0x7ffff8,%esi
0x0000000108a95627: cmp    $0x0,%esi
0x0000000108a9562a: je     0x0000000108a959c9
0x0000000108a95630: mov    %rax,%rdx
0x0000000108a95633: movabs $0x1214df850,%rsi  ;   {metadata(method data for {method} {0x0000000121341738} '<init>' '(I)V' in 'java/lang/Integer')}
0x0000000108a9563d: addq   $0x1,0x108(%rsi)
0x0000000108a95645: movabs $0x1214df720,%rdx  ;   {metadata(method data for {method} {0x000000012133a9d8} '<init>' '()V' in 'java/lang/Number')}
0x0000000108a9564f: mov    0xdc(%rdx),%esi
0x0000000108a95655: add    $0x8,%esi
0x0000000108a95658: mov    %esi,0xdc(%rdx)
0x0000000108a9565e: movabs $0x12133a9d8,%rdx  ;   {metadata({method} {0x000000012133a9d8} '<init>' '()V' in 'java/lang/Number')}
0x0000000108a95668: and    $0x7ffff8,%esi
0x0000000108a9566e: cmp    $0x0,%esi
0x0000000108a95671: je     0x0000000108a959e0
0x0000000108a95677: mov    %rax,%rdx
0x0000000108a9567a: movabs $0x1214df720,%rsi  ;   {metadata(method data for {method} {0x000000012133a9d8} '<init>' '()V' in 'java/lang/Number')}
0x0000000108a95684: addq   $0x1,0x108(%rsi)
0x0000000108a9568c: movabs $0x12140ddf8,%rdx  ;   {metadata(method data for {method} {0x000000012129d480} '<init>' '()V' in 'java/lang/Object')}
0x0000000108a95696: mov    0xdc(%rdx),%esi
0x0000000108a9569c: add    $0x8,%esi
0x0000000108a9569f: mov    %esi,0xdc(%rdx)
0x0000000108a956a5: movabs $0x12129d480,%rdx  ;   {metadata({method} {0x000000012129d480} '<init>' '()V' in 'java/lang/Object')}
0x0000000108a956af: and    $0x7ffff8,%esi
0x0000000108a956b5: cmp    $0x0,%esi
0x0000000108a956b8: je     0x0000000108a959f7
0x0000000108a956be: mov    %ebx,0xc(%rax)     ;*putfield value
                                              ;- java.lang.Integer::<init>@6 (line 850)
                                              ;- SwitchTest::daysInMonth@140 (line 30)
```

invocation cnt of Integer::<init> in daysInMonth for inline

invocation cnt in Integer::<init> + trigger its C2 (tier 4)

invocation cnt of Number::<init> in Int::<init> for inline

invocation cnt in Number::<init> + trigger its C2 (tier 4)

invocation cnt of Object::<init> in Numb::<init> for inline

invocation cnt in Object::<init> + trigger its C2 (tier 4)

RAX.value = EBX (retVal)

continues on the next slide

JVM – Example 2 – daysInMonth Assembly Code – Tier 3

final cleanup and return, RAX contains return value (pointer to Integer instance)

```
0x0000000108a956c1: add    $0x80,%rsp
0x0000000108a956c8: pop    %rbp
0x0000000108a956c9: test   %eax,-0x214c5cf(%rip)        # 0x0000000106949100
                                                ;   {poll_return}
0x0000000108a956cf: retq                        ;*areturn
                                                ; - SwitchTest::daysInMonth@143 (line 30)
```

stack dealocation, reload register

safepoint poll check

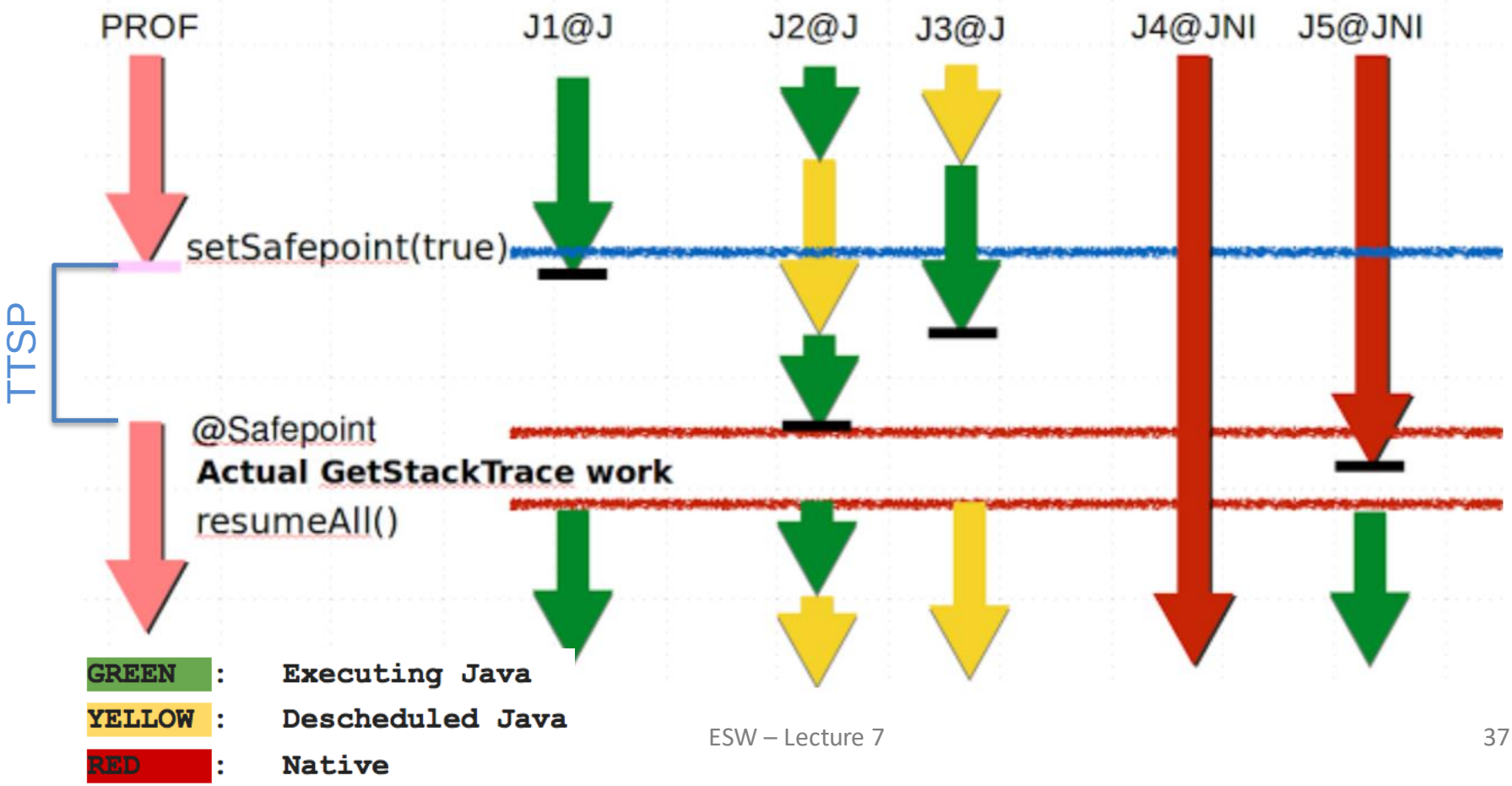
- **Ordinary Object Pointer** (Oop) – flexible reference to an object
- **safepoint** – Oops in perfectly described state by OopMap (GCmaps)
  - Oop can be **safely manipulated externally** while thread is suspended
  - **in interpreted mode** – between any 2 byte codes
  - **in C1/C2 compiled** – end of all methods (not in-lined), non-counted loop back edge,
    during JVM run-time call
  - parked, blocked on IO, monitor or lock
  - while running JNI (do not need thread suspension)
  - **global safepoint (all threads)** – stop the world
    - GC, print threads, thread dumps, heap dump, get all stack trace
    - class redefinition (e.g. instrumentation), debug
    - enableBiasedLocking, RevokeBias (removed since Java 17)
  - **local safepoint (just executing thread)**
    - de-optimization, OSR

JVM – Time To Safe Point

» **Time To Safe Point** (TTSP) – how long it takes to enter safepoint

-XX:+PrintSafepointStatistics -XX:+PrintGCApplicationStoppedTime -XX:PrintSafepointStatisticsCount=1

TTSP overhead in profiler while calling GetStackTrace example with 5 threads:



JVM – Example 2 – daysInMonth Assembly Code – Tier 4

tier 4 – C2 compiler – no profile counters

because: count="5376" iicount="5376" **hot_count="5376"**

stack initialization, **use lookup table jump** for table switch

```
[Entry Point]
[Verified Entry Point]
  # {method} {0x000000012169d568} 'daysInMonth' '(II)Ljava/lang/Integer;' in 'SwitchTest'
  # parm0:    rsi       = int
  # parm1:    rdx       = int
  #           [sp+0x20]  (sp of caller)
  0x0000000108a97020: mov    %eax,-0x14000(%rsp)  ;   {no_reloc}
  0x0000000108a97027: push   %rbp
  0x0000000108a97028: sub    $0x10,%rsp          ;*synchronization entry
                                                 ; - SwitchTest::daysInMonth@-1 (line 7)

  0x0000000108a9702c: mov    %esi,%r11d
  0x0000000108a9702f: dec    %r11d
  0x0000000108a97032: cmp    $0xc,%r11d
  0x0000000108a97036: jae    0x0000000108a9704a
  0x0000000108a97038: movslq %esi,%r10
  0x0000000108a9703b: movabs $0x108a96fc0,%r11   ;   {section_word}
  0x0000000108a97045: jmpq   *-0x8(%r11,%r10,8)  ;*tableswitch
                                                 ; - SwitchTest::daysInMonth@1 (line 7)
```

month, year

default (>=12)

continues on the next slide …

```
    135   18     b  4       SwitchTest::daysInMonth (144 bytes)
Decoding compiled method 0x0000000108a96e50:
Code:
[Constants]
  0x0000000108a96fc0 (offset:    0): 0x08a97083   0x0000000108a97083
  0x0000000108a96fc4 (offset:    4): 0x00000001
  0x0000000108a96fc8 (offset:    8): 0x08a9706c   0x0000000108a9706c
  0x0000000108a96fcc (offset:   12): 0x00000001
  0x0000000108a96fd0 (offset:   16): 0x08a97083   0x0000000108a97083
  0x0000000108a96fd4 (offset:   20): 0x00000001
  0x0000000108a96fd8 (offset:   24): 0x08a9708a   0x0000000108a9708a
  0x0000000108a96fdc (offset:   28): 0x00000001
  0x0000000108a96fe0 (offset:   32): 0x08a97083   0x0000000108a97083
  0x0000000108a96fe4 (offset:   36): 0x00000001
  0x0000000108a96fe8 (offset:   40): 0x08a9708a   0x0000000108a9708a
  0x0000000108a96fec (offset:   44): 0x00000001
  0x0000000108a96ff0 (offset:   48): 0x08a97083   0x0000000108a97083
  0x0000000108a96ff4 (offset:   52): 0x00000001
  0x0000000108a96ff8 (offset:   56): 0x08a97083   0x0000000108a97083
  0x0000000108a96ffc (offset:   60): 0x00000001
  0x0000000108a97000 (offset:   64): 0x08a9708a   0x0000000108a9708a
  0x0000000108a97004 (offset:   68): 0x00000001
  0x0000000108a97008 (offset:   72): 0x08a97083   0x0000000108a97083
  0x0000000108a9700c (offset:   76): 0x00000001
  0x0000000108a97010 (offset:   80): 0x08a9708a   0x0000000108a9708a
  0x0000000108a97014 (offset:   84): 0x00000001
  0x0000000108a97018 (offset:   88): 0x08a97083   0x0000000108a97083
  0x0000000108a9701c (offset:   92): 0x00000001
```

JVM – Example 2 – daysInMonth Assembly Code – Tier 4

target for month=4

Integer.<init>, Number.<init>, Object.<init> - iicount="5376" -> **Inline (hot)**

optimized branching, inlined TLAB allocation, inlined constructors, no nulling, caching optimization

```
0x0000000108a9708a: mov    $0x1e,%ebp          ;*goto
                                               ; - SwitchTest::daysInMonth@105 (line 26)

0x0000000108a9708f: mov    0x60(%r15),%rax
0x0000000108a97093: mov    %rax,%r10
0x0000000108a97096: add    $0x10,%r10
0x0000000108a9709a: cmp    0x70(%r15),%r10
0x0000000108a9709e: jae    0x0000000108a97124
0x0000000108a970a4: mov    %r10,0x60(%r15)
0x0000000108a970a8: prefetchnta 0xc0(%r10)
0x0000000108a970b0: mov    $0xf8002264,%r10d   ;   {metadata('java/lang/Integer')}
0x0000000108a970b6: shl    $0x3,%r10
0x0000000108a970ba: mov    0xa8(%r10),%r10
0x0000000108a970c1: mov    %r10,(%rax)
0x0000000108a970c4: movl   $0xf8002264,0x8(%rax)  ;*new
                                               ; - SwitchTest::daysInMonth@135 (line 30)
                                               ;   {metadata('java/lang/Integer')}
0x0000000108a970cb: mov    %ebp,0xc(%rax)      ;*synchronization entry
                                               ; - SwitchTest::daysInMonth@-1 (line 7)

0x0000000108a970ce: add    $0x10,%rsp
0x0000000108a970d2: pop    %rbp
0x0000000108a970d3: test   %eax,-0x214e0d9(%rip)        # 0x0000000106949000
                                               ;   {poll_return}
0x0000000108a970d9: retq
```

EBP=30 is retVal

TLAB Integer object allocation, ref in **RAX**

cache optimization 3 cache lines ahead

MarkWord fetch from class and then store

compressed OOP to Integer class

RAX.value = EBX (retVal)

final cleanup

RAX contains **return value** (pointer to Integer instance)

JVM – Example 2 – daysInMonth Assembly Code – Tier 4

target for default

class IllegalArgumentException no profile -> uncommon -> reinterpret

remap inputs, return back to reinterpreter

```
0x0000000108a9704a: mov    %esi,%ebp
0x0000000108a9704c: mov    $0x2,%esi
0x0000000108a97051: xchg   %ax,%ax
0x0000000108a97053: callq  0x000000010898b1a0  ; OopMap{off=56}
                                              ;*new  ; - SwitchTest::daysInMonth@108 (line 28)
                                              ;   {runtime_call}
0x0000000108a97058: callq  0x0000000107e7e33c  ;*new
                                              ; - SwitchTest::daysInMonth@108 (line 28)
                                              ;   {runtime_call}
```

then tier 3 code version is discarded

```
138   17       3       SwitchTest::daysInMonth (144 bytes)   made not entrant
```

JVM – Example 2 – compute Assembly Code – Tier 4 OSR

OSR @10 – On Stack Replacement at bytecode 10

tier 4 – C2 (before there was tier 3 OSR @10 because 60416 loops and tier 3)

because: backedge_count="101376" **hot_count="101376"**

```
147   21 %  b  4       SwitchTest::compute @ 10 (35 bytes)
```

copy 4 locals on stack from tier3 OSR @10 to regs

```
StackMapTable: number_of_entries = 2
  frame_type = 255 /* full_frame */
    offset_delta = 10
    locals = [ int, int, int, int ]
    stack = []
  frame_type = 250 /* chop */
    offset_delta = 22
```

```
private static int compute() {
    int month = 4;
    int year = 2000;
    int o=0;
    for (int i=0; i<1_000_000; i++) {
        o+=daysInMonth(month, year);
    }
    return o;
}
```

```
0x0000000108a98370: mov    %eax,-0x14000(%rsp)
0x0000000108a98377: push   %rbp
0x0000000108a98378: sub    $0x20,%rsp
0x0000000108a9837c: mov    (%rsi),%ebx
0x0000000108a9837e: mov    0x18(%rsi),%ebp
0x0000000108a98381: mov    0x10(%rsi),%r13d
0x0000000108a98385: mov    0x8(%rsi),%r14d
0x0000000108a98389: mov    %rsi,%rdi
```

continues on the next slide …

RSI compiled stack of tier 3 **OSR** @10

```
 0: iconst_4
 1: istore_0
 2: sipush        2000
 5: istore_1
 6: iconst_0
 7: istore_2
 8: iconst_0
 9: istore_3
10: iload_3
11: ldc           #12
13: if_icmpge     33
16: iload_2
17: iload_0
18: iload_1
19: invokestatic  #13
22: invokevirtual #14
25: iadd
26: istore_2
27: iinc          3, 1
30: goto          10
33: iload_2
34: ireturn
```

JVM – Example 2 – compute Assembly Code – Tier 4 OSR

loop criteria

```
for (int i=0; i<1_000_000; i++) {
    o+=daysInMonth(month, year);
}
```

```
0x0000000108a98423: cmp    $0xf4240,%ebx
0x0000000108a98429: jge    0x0000000108a98450  ;*if_icmpge
                                               ; - SwitchTest::compute@13 (line 37)

0x0000000108a9842b: inc    %ebx                ;*iinc
                                               ; - SwitchTest::compute@27 (line 37)
```

EBX is local i; 0xF4240 = 1 000 000

then there is **inlined** tier 4 daysOfMonth (lookup jump) because the call is **hot**

ending with addition into accumulator o

```
0x0000000108a9841a: add    %r8d,%r14d          ; OopMap{off=189}
                                               ;*goto
                                               ; - SwitchTest::compute@30 (line 37)
```

reinterpret on end of cycle jump (unstable if bytecode), save 3 locals to stack

```
0x0000000108a98450: mov    $0xffffff65,%esi
0x0000000108a98455: mov    %r13d,(%rsp)
0x0000000108a98459: mov    %r14d,0x4(%rsp)
0x0000000108a9845e: mov    %ebx,0xc(%rsp)
0x0000000108a98462: nop
0x0000000108a98463: callq  0x000000010898b1a0  ; OopMap{off=264}
                                               ;*if_icmpge
                                               ; - SwitchTest::compute@13 (line 37)
                                               ;   {runtime_call}
0x0000000108a98468: callq  0x0000000107e7e33c  ;   {runtime_call}
```

```
StackMapTable: number_of_entries = 2
  frame_type = 255 /* full_frame */
    offset_delta = 10
    locals = [ int, int, int, int ]
    stack = []
  frame_type = 250 /* chop */
    offset_delta = 22
```

JVM – Example 2 – compute Assembly Code – Tier 4

tier 4 – C2

because: count="2" **backedge_count="150528"**

use combination of **full inline**, **dead code elimination**, **object escape**, **loop invariant hoisting**, **strength reduction**

```
   157   23    b  4       SwitchTest::compute (35 bytes)
Decoding compiled method 0x0000000108a97f90:
Code:
[Entry Point]
[Verified Entry Point]
[Constants]
  # {method} {0x000000012169d638} 'compute' '()I' in 'SwitchTest'
  #           [sp+0x20]  (sp of caller)
  0x0000000108a980c0: sub    $0x18,%rsp
  0x0000000108a980c7: mov    %rbp,0x10(%rsp)    ;*synchronization entry
                                                ; - SwitchTest::compute@-1 (line 34)

  0x0000000108a980cc: mov    $0x1c9c380,%eax
  0x0000000108a980d1: add    $0x10,%rsp
  0x0000000108a980d5: pop    %rbp
  0x0000000108a980d6: test   %eax,-0x214f0dc(%rip)        # 0x0000000106949000
                                                ;   {poll_return}
  0x0000000108a980dc: retq
```

30 000 000

RAX contains **return value** (primitive int)

Java Virtual Machine – Performance

» **requires warm-up to utilize benefits of C2 (or C1)**

» compilers cannot do all magic -> **write better algorithms**

» **32-bit vs 64 bits JVMs**

- 32-bit (max ~3GB heap)
  - smaller memory footprint
  - slower long & double operations
- 64-bit max 32GB virtual memory (with default ObjectAlignmentInBytes)
  - faster performance for long & double
  - slight increase of memory footprint
  - compressed OOPs are slightly slower for references upon usage
  - compressed OOPs less memory -> less frequent GC -> faster program
- 64-bit >32GB virtual memory (large heap)
  - fast reference usage
  - wasting a lot of memory (48GB ~32GB with compressed OOPs)

Java Virtual Machine – CPU and Memory Profiling

- **profiling**
  - CPU – time spent in methods
  - memory – usage, allocations
- **modes**
  - sampling
    - periodic sampling of stacks of running threads
    - no invocation counts, no 100% accuracy (various sampling errors)
    - no bytecode (& assembly code) modifications
    - **1-2% impact to standard performance** (TTSP, thread dumps, analysis)
  - tracing (instrumetation) - method entry, exit, traceObjAllocations
    - **instrumented bytecode -> affected performance -> affected compiler optimizations**
- **visualvm**
  - JVM monitoring, troubleshooting and profiling tool
  - included in JDK 6-8 (jvisualvm), now standalone tool

JVM – Example 2 – CPU Tracing of daysOfMonth

assembly code of tier 4 – C2 (before there was very complex tier 3)

inlined daysInMonth **rootMethodEntry** tracking

```
# {method} {0x000000012489e838} 'daysInMonth' '(II)Ljava/lang/Integer;' in 'SwitchTest'
# parm0:    rsi       = int
# parm1:    rdx       = int
#           [sp+0x70]  (sp of caller)
0x000000010c08aa80: mov    %eax,-0x14000(%rsp)  ;   {no_reloc}
0x000000010c08aa87: push   %rbp
0x000000010c08aa88: sub    $0x60,%rsp         ;*synchronization entry
                                              ; - SwitchTest::daysInMonth@-1 (line 7)

0x000000010c08aa8c: mov    %edx,0x4(%rsp)
0x000000010c08aa90: mov    %esi,(%rsp)
0x000000010c08aa93: movabs $0x76c73a180,%r10  ;   {oop(a 'java/lang/Class' = 'org/netbeans/lib/profiler/server/ProfilerRuntimeCPU')}
0x000000010c08aa9d: movzbl 0x82(%r10),%r11d   ;*getstatic recursiveInstrumentationDisabled
                                              ; - org.netbeans.lib.profiler.server.ProfilerRuntimeCPUFullInstr::rootMethodEntry@0 (line 189)
                                              ; - SwitchTest::daysInMonth@3 (line 7)

0x000000010c08aaa5: test   %r11d,%r11d
0x000000010c08aaa8: jne    0x000000010c08b075  ;*ifeq
                                              ; - org.netbeans.lib.profiler.server.ProfilerRuntimeCPUFullInstr::rootMethodEntry@3 (line 189)
                                              ; - SwitchTest::daysInMonth@3 (line 7)

0x000000010c08aaae: movabs $0x76c73e220,%r10  ;   {oop(a 'java/lang/Class' = 'org/netbeans/lib/profiler/server/ThreadInfo')}
0x000000010c08aab8: mov    0x78(%r10),%r8d    ;*getstatic lastThreadInfo
                                              ; - org.netbeans.lib.profiler.server.ThreadInfo::getThreadInfo@4 (line 244)
                                              ; - org.netbeans.lib.profiler.server.ProfilerRuntimeCPUFullInstr::rootMethodEntry@7 (line 193)
                                              ; - SwitchTest::daysInMonth@3 (line 7)

0x000000010c08aabc: mov    0x40(%r12,%r8,8),%ebp  ;*getfield thread
                                              ; - org.netbeans.lib.profiler.server.ThreadInfo::getThreadInfo@9 (line 246)
                                              ; - org.netbeans.lib.profiler.server.ProfilerRuntimeCPUFullInstr::rootMethodEntry@7 (line 193)
```

749 Bytes of assembly code for each **rootMethodEntry**

JVM – Example 2 – CPU Tracing of daysOfMonth

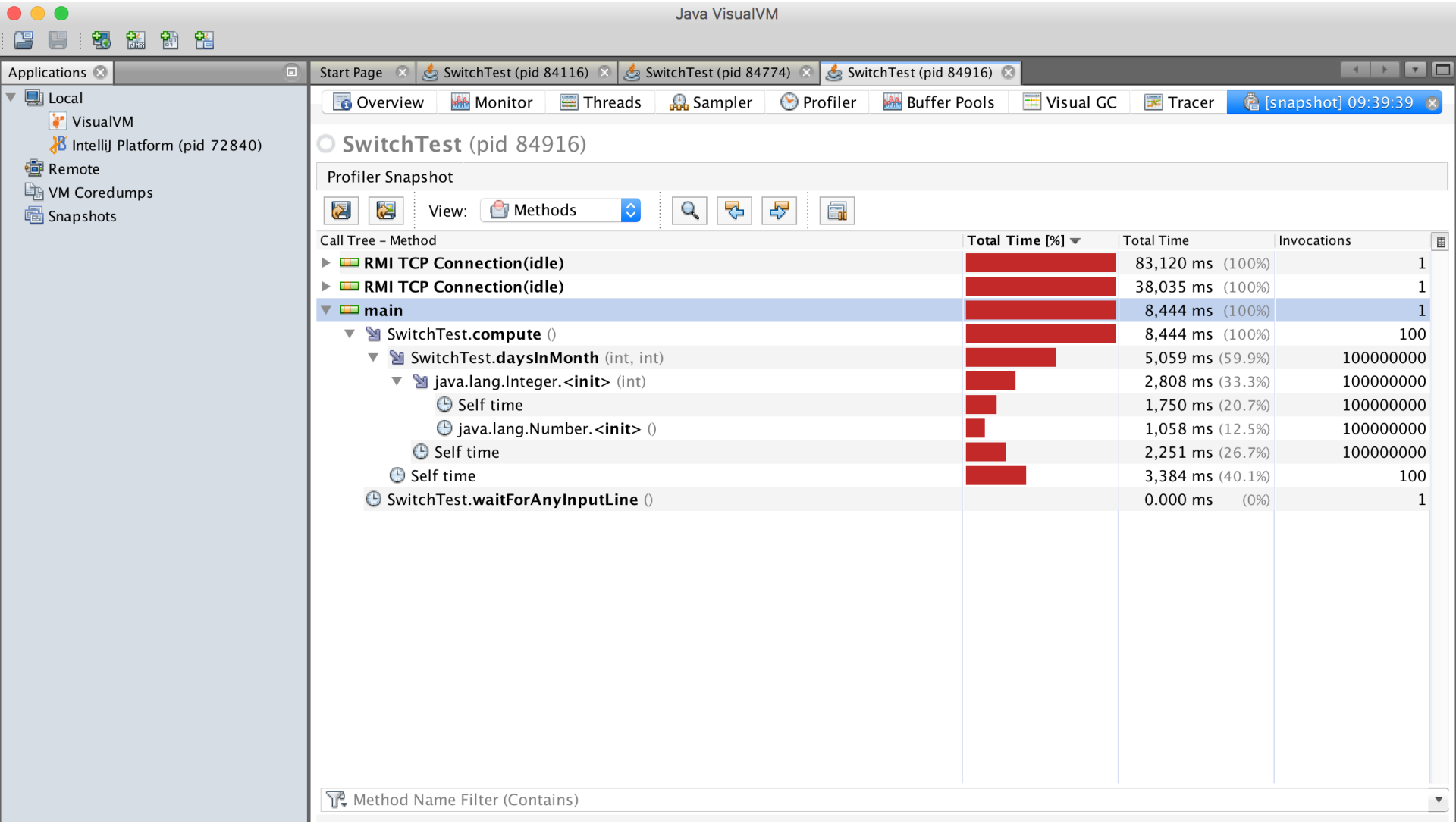
additional **rootMethodEntry** and **rootMethodExit** trackings for
Integer::<init> and Number::<init>

inlined rootMethodExit after Integer instance.value = retVal

```
0x000000010c08b73a: mov    0x8(%rsp),%r11
0x000000010c08b73f: mov    %r10d,0xc(%r11)    ;*synchronization entry
                                              ; - org.netbeans.lib.profiler.server.ProfilerRuntimeCPUFullInstr::methodExit@-1 (line 147)
                                              ; - java.lang.Integer::<init>@20 (line 851)
                                              ; - SwitchTest::daysInMonth@148 (line 30)

0x000000010c08b743: movabs $0x76c73a180,%r10  ;   {oop(a 'java/lang/Class' = 'org/netbeans/lib/profiler/server/ProfilerRuntimeCPU')}
0x000000010c08b74d: movzbl 0x82(%r10),%ebp    ;*getstatic recursiveInstrumentationDisabled
                                              ; - org.netbeans.lib.profiler.server.ProfilerRuntimeCPUFullInstr::methodExit@0 (line 147)
                                              ; - java.lang.Integer::<init>@20 (line 851)
                                              ; - SwitchTest::daysInMonth@148 (line 30)

0x000000010c08b755: test   %ebp,%ebp
0x000000010c08b757: jne    0x000000010c08bdd1  ;*ifeq
                                              ; - org.netbeans.lib.profiler.server.ProfilerRuntimeCPUFullInstr::methodExit@3 (line 147)
                                              ; - java.lang.Integer::<init>@20 (line 851)
                                              ; - SwitchTest::daysInMonth@148 (line 30)

0x000000010c08b75d: movabs $0x76c73e220,%r10  ;   {oop(a 'java/lang/Class' = 'org/netbeans/lib/profiler/server/ThreadInfo')}
0x000000010c08b767: mov    0x78(%r10),%ecx    ;*getstatic lastThreadInfo
                                              ; - org.netbeans.lib.profiler.server.ThreadInfo::getThreadInfo@4 (line 244)
                                              ; - org.netbeans.lib.profiler.server.ProfilerRuntimeCPUFullInstr::methodExit@7 (line 151)
                                              ; - java.lang.Integer::<init>@20 (line 851)
                                              ; - SwitchTest::daysInMonth@148 (line 30)

0x000000010c08b76b: mov    0x40(%r12,%rcx,8),%ebp  ;*invokestatic currentThread
                                              ; - org.netbeans.lib.profiler.server.ThreadInfo::getThreadInfo@0 (line 243)
                                              ; - org.netbeans.lib.profiler.server.ProfilerRuntimeCPUFullInstr::rootMethodEntry@7 (line 19
                                              08c0b9
```

313 Bytes of assembly code for each **rootMethodEntry**

JVM – Example 2 – CPU Tracing Outcome



JVM – Example 2 – Profiling Performance

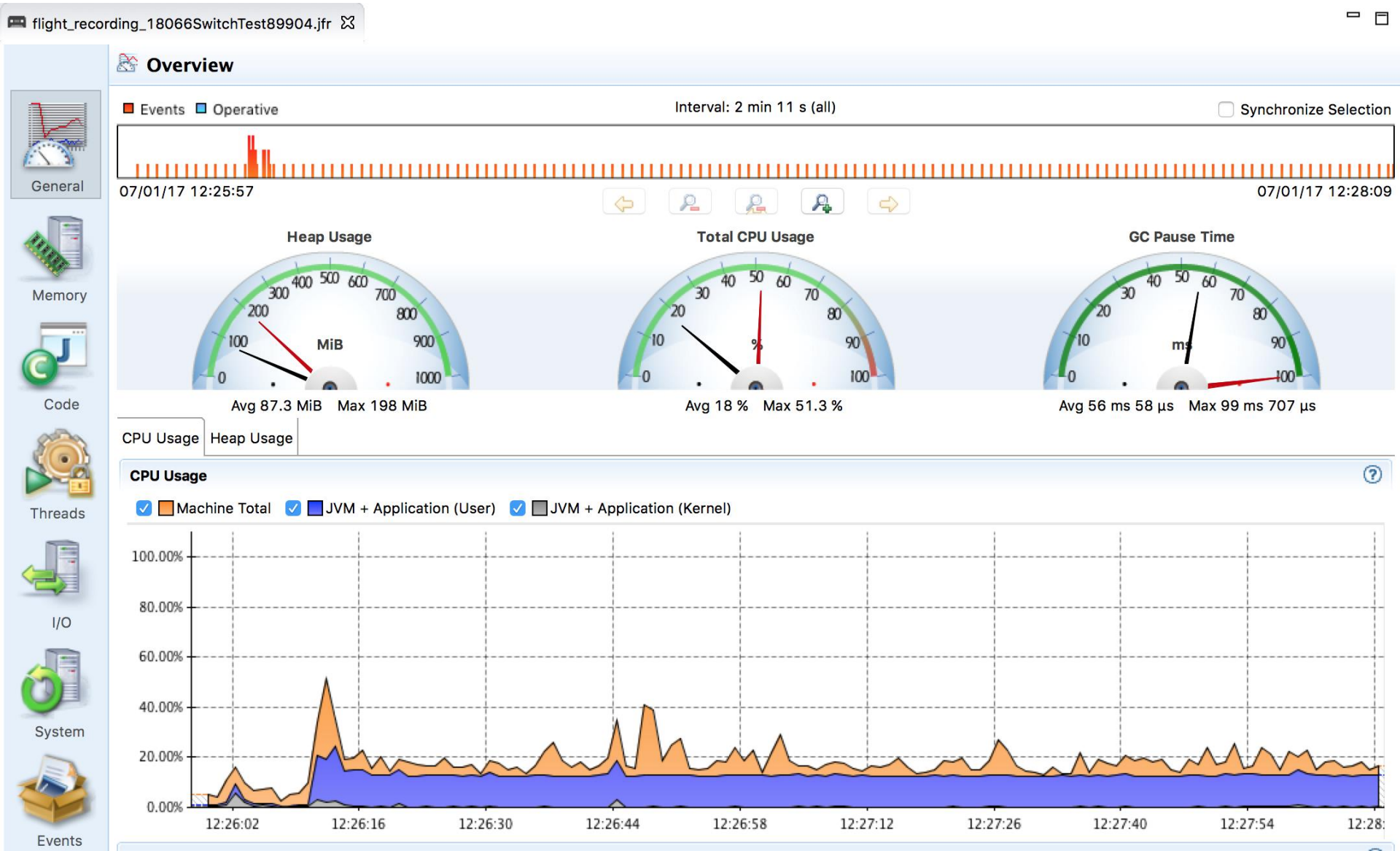
» CPU **tracing** of compute method results into **much slower code**
  - no object escape from daysInMonth call
  - no invariant hoisting
  - no strength reduction (full loop remains there)

» object allocation tracing is similar with **traceObjAlloc** injected calls

» **recommended approach**
  - do sampling first
  - identify performance bottlenecks (where most time is spent)
    - it could be outside of JVM (e.g. latency of external DB, file system)
  - focus with tracing just to identified parts

JVM – Java Mission Control

jmc – included in JDKs, sampling in Flight recorder



Approach to Performance Testing

- **test real application** – ideally the way it is used
  - **microbenchmarks** – measure very small units
    - warm-up – to measure real code, not compilers itself, biased locks
      - keep in mind caching
    - beware of compilers – use results, reordering of operations
    - synchronization – multi-threaded benchmarks
    - vary pre-calculated parameters affecting complexity – different optimization in reality
  - **macrobenchmarks** – measure application input/output
    - least performing component affects the whole application

- **understand throughput, elapsed and response time**
  - outliers can occur – e.g. GC
  - use existing generators than writing own

Approach to Performance Testing

» **understand variability** – changes over time
  - internal state
  - background effects – load, network
  - probabilistic analysis – works with uncertainty

» **test early, test often** – ideally part of development cycle
  - ideally some properly repeated benchmarking
  - automate tests – scripted
  - proper test coverage of functionality and inputs
  - test on target system – different code on different systems