From Java Code to Machine Code

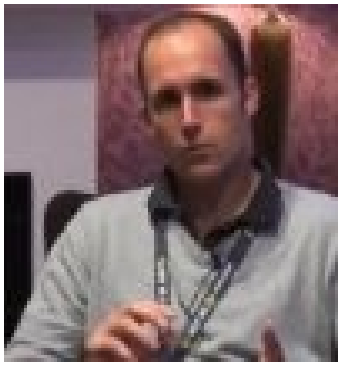
Understanding how to write optimizeable code

Chris Bailey
IBM Runtime Technologies

Chris Bailey

IBM Runtime Monitoring and Diagnostics Architect

- 14 years working with Java and JVM technologies
- 14 months working with Node.js and V8



Current Role(s):

- IBM Java monitoring and diagnostics
- Node Application Metrics project lead

Node Foundation Member
Benchmarking and Post-mortem WGs

JavaOne RockStar
Author on performance and memory analysis

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Anatomy of a Class File

Anatomy of a Java Class File

```
struct Class_File_Format {
    u4 magic_number;
    u2 minor_version;
    u2 major_version;

    u2 constant_pool_count;
    cp_info constant_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];
}
```

Anatomy of a Java Class File

```
public class MyClass {String[] args) {
    public int myField = 48;
}
```

```
public int myField;
  flags: ACC_PUBLIC

public MyClass();
  flags: ACC_PUBLIC
  Code:
  stack=2, locals=1, args_size=1
    0: aload_0
    1: invokespecial #10
    4: aload_0
    5: bipush        48
    7: putfield      #12
   10: return
  LineNumberTable:
    line 2: 0
    line 3: 4
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  LocalVariableTable:
      0      11     0  this   LmyClass;
```

```
flags: ACC_PUBLIC, ACC_SUPER
Constant pool:
   #1 = Class              #2
   #2 = Utf8                 MyClass
   #3 = Class                #4
   #4 = Utf8                 java/lang/Object
   #5 = Utf8                 myField
   #6 = Utf8                 I
   #7 = Utf8                 <init>
   #8 = Utf8                 ()V
   #9 = Utf8                 Code
  #10 = Methodref            #4.#11
  #11 = NameAndType          #7:#8
  #12 = Fieldref             #1.#13
  #13 = NameAndType          #5:#6
  #14 = Utf8                 LineNumberTable
  #15 = Utf8                 LocalVariableTable
  #16 = Utf8                 this
  #17 = Utf8                 LmyClass;
  #18 = Utf8                 SourceFile
  #19 = Utf8                 MyClass.java
```

Constant Pool Resolution

Anatomy of a Java Class File: Constant Pool

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1	2	3	4
#2 (Class)	**MyClass** (Utf8)	**#4** (Class)	**java/lang/Object** (Utf8)
5	6	7	8
MyField (Utf8)	**I** (Utf8)	**<init>** (Utf8)	**()V** (Utf8)
9	10	11	12
Code (Utf8)	**#4.#11** (MethodRef)	**#7.#8** (NameAndType)	**#1.#13** (Fieldref)
13	14	15	16
#5.#6 (NameAndType)	**LineNumberTable** (Utf8)	**LocalVariableTable** (Utf8)	**this** (Utf8)
17	18	19	
LmyClass (Utf8)	**SourceFile** (Utf8)	**MyClass.java** (Utf8)	

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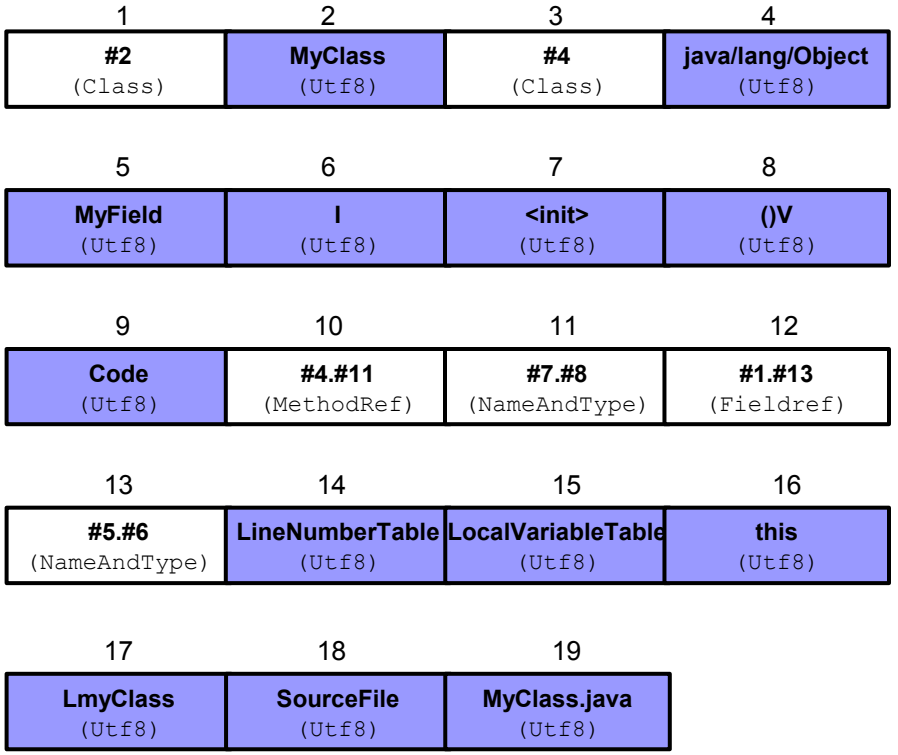

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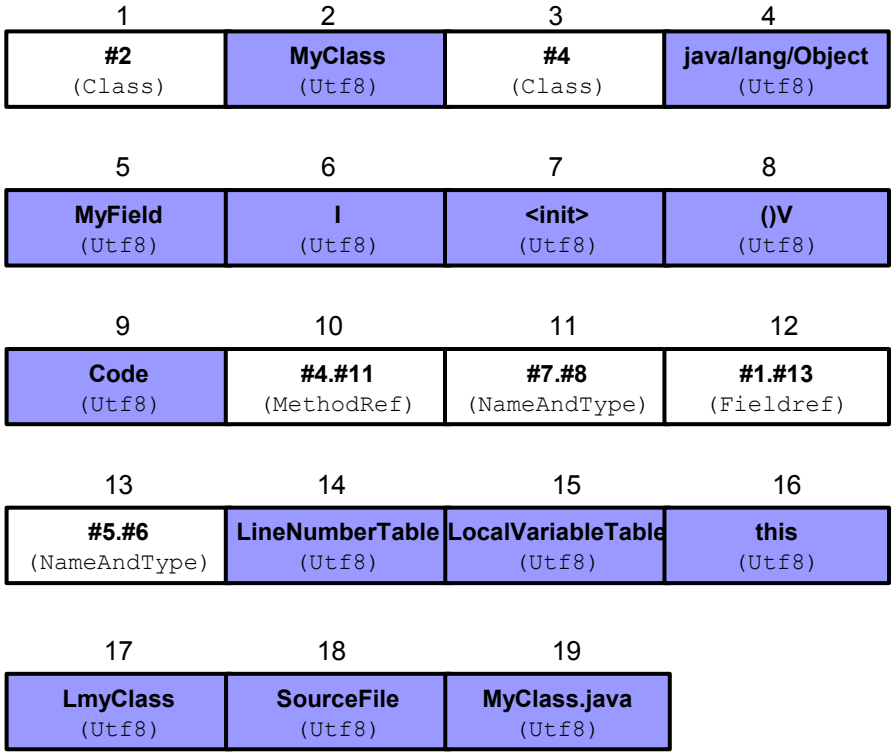

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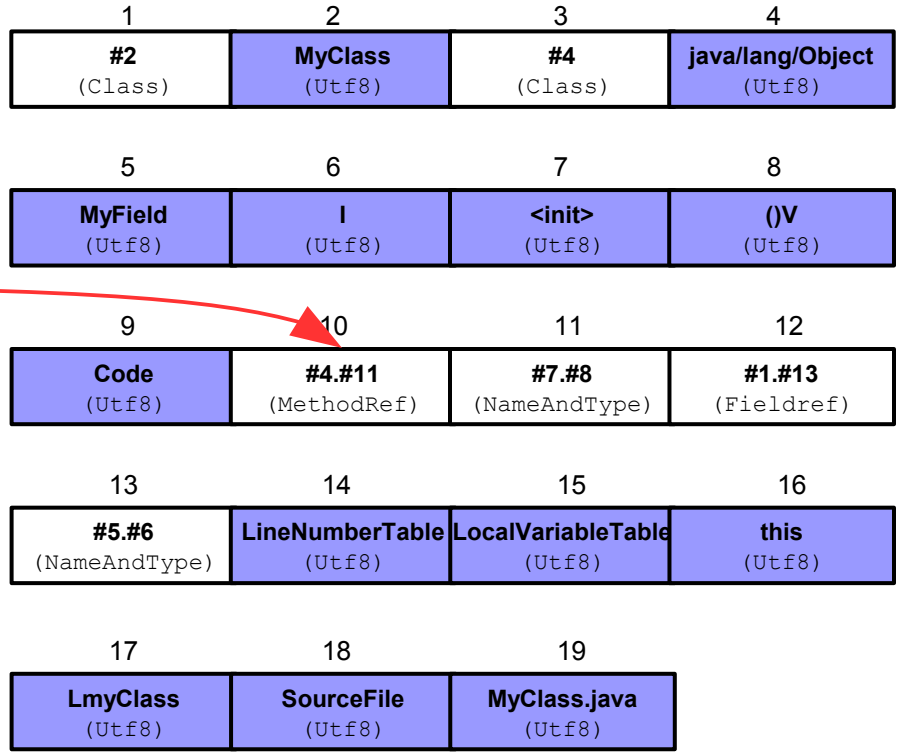

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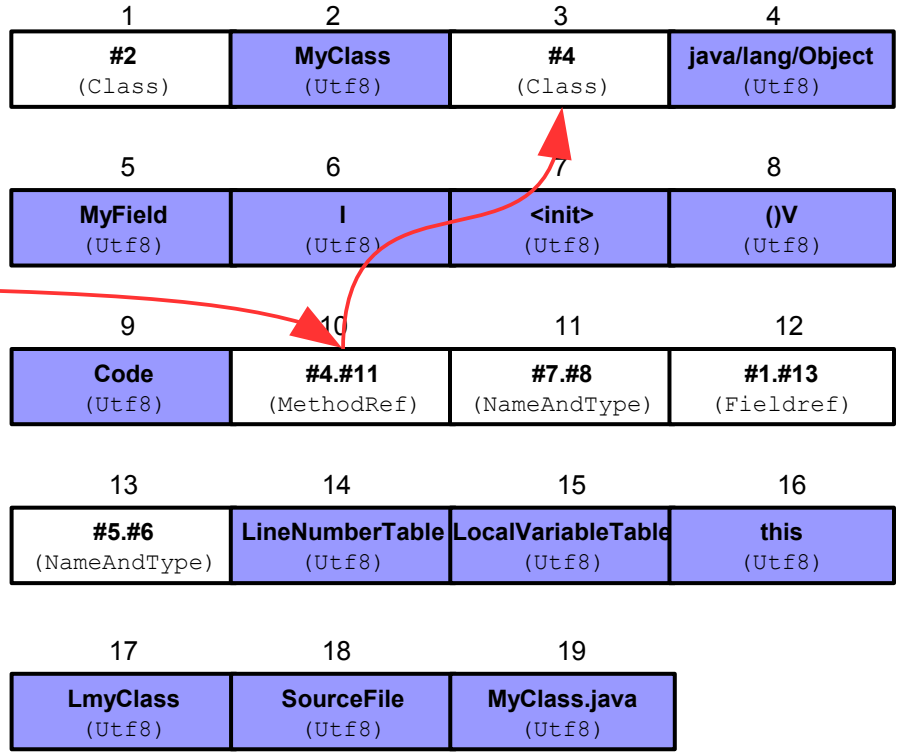

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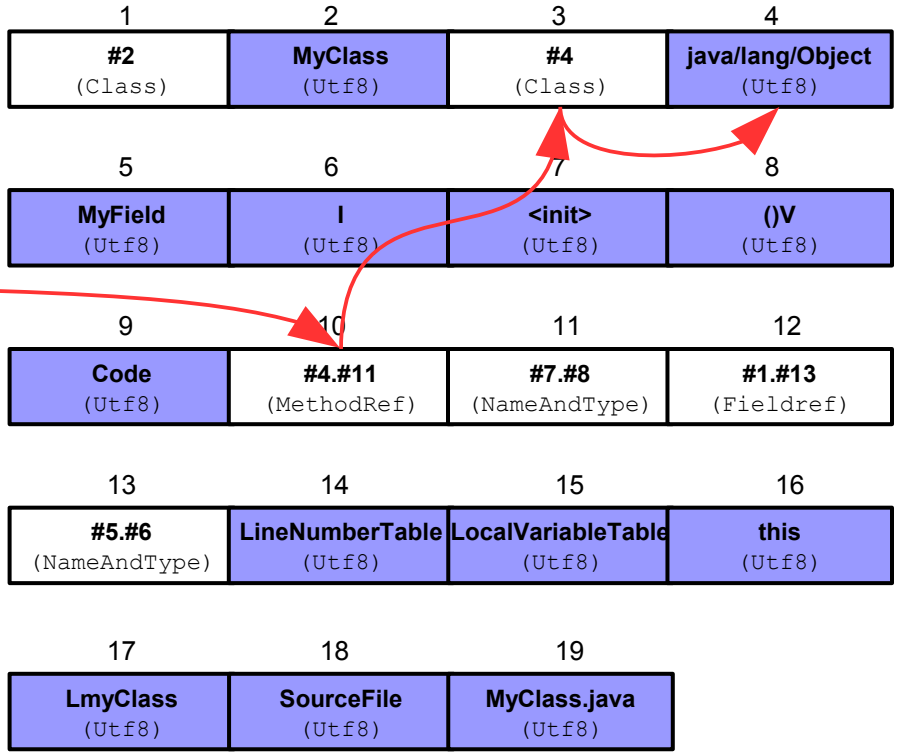

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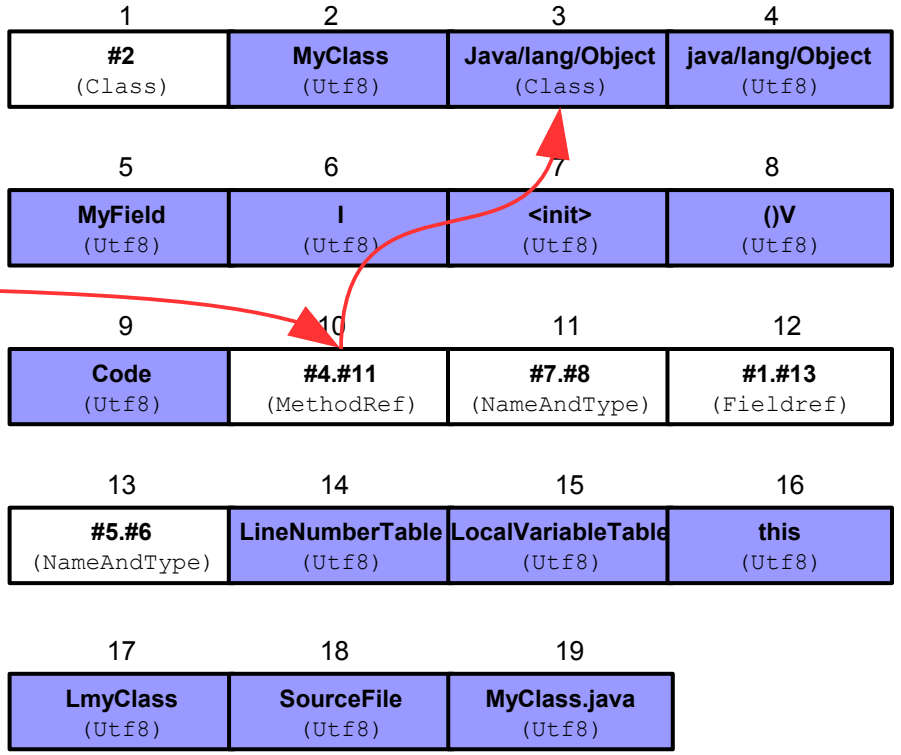

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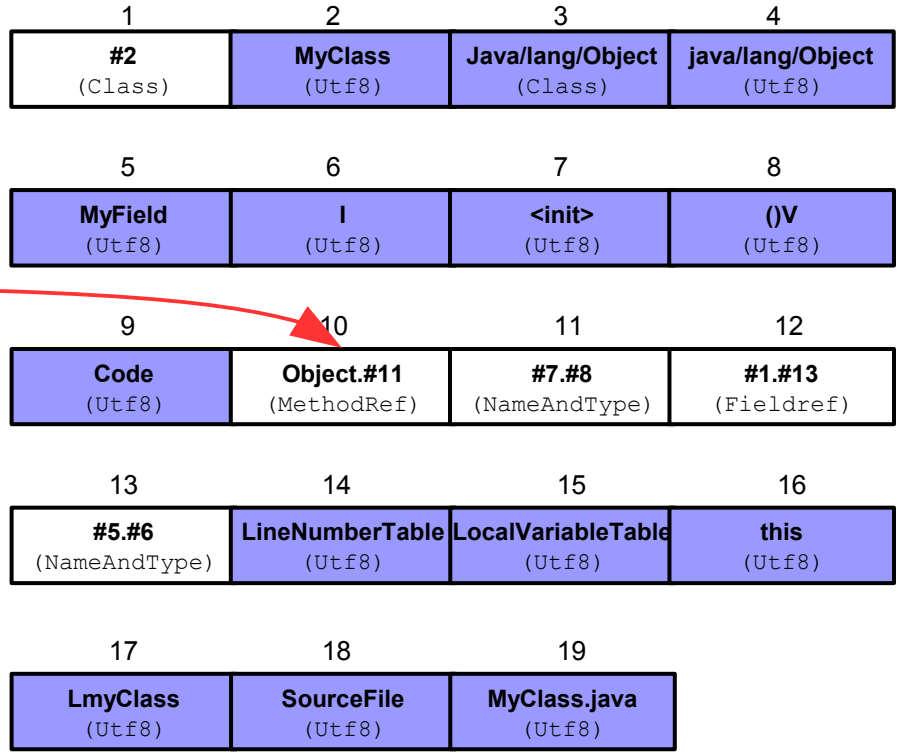

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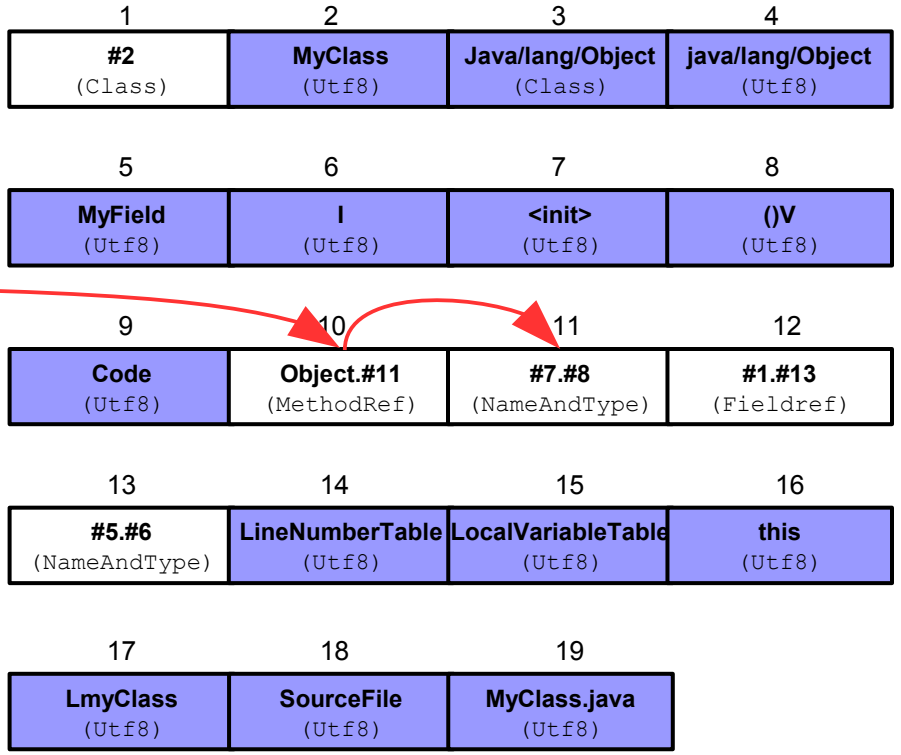

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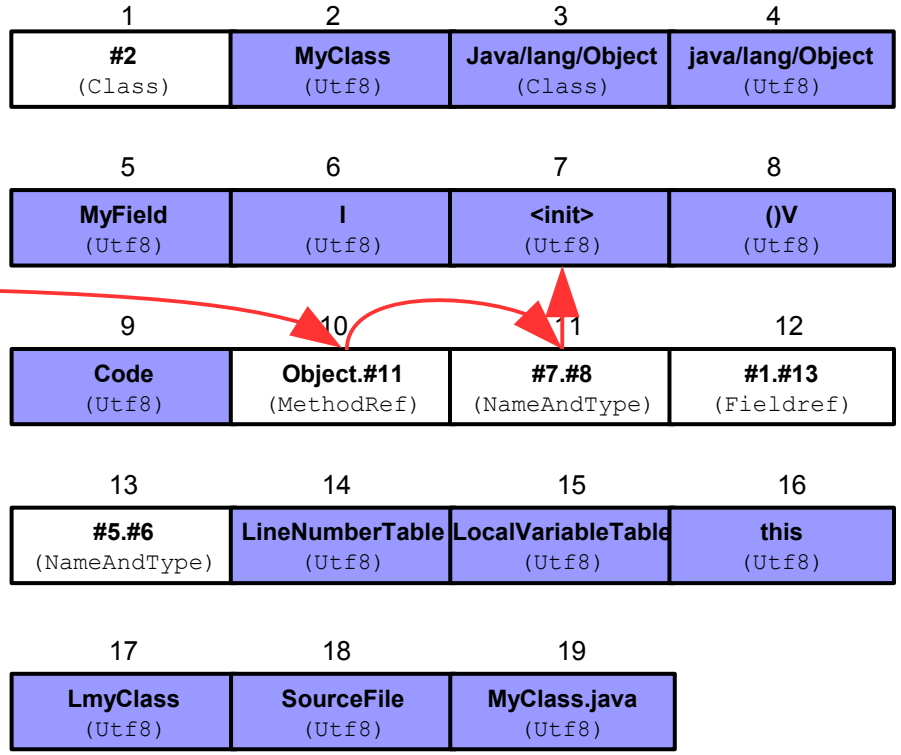

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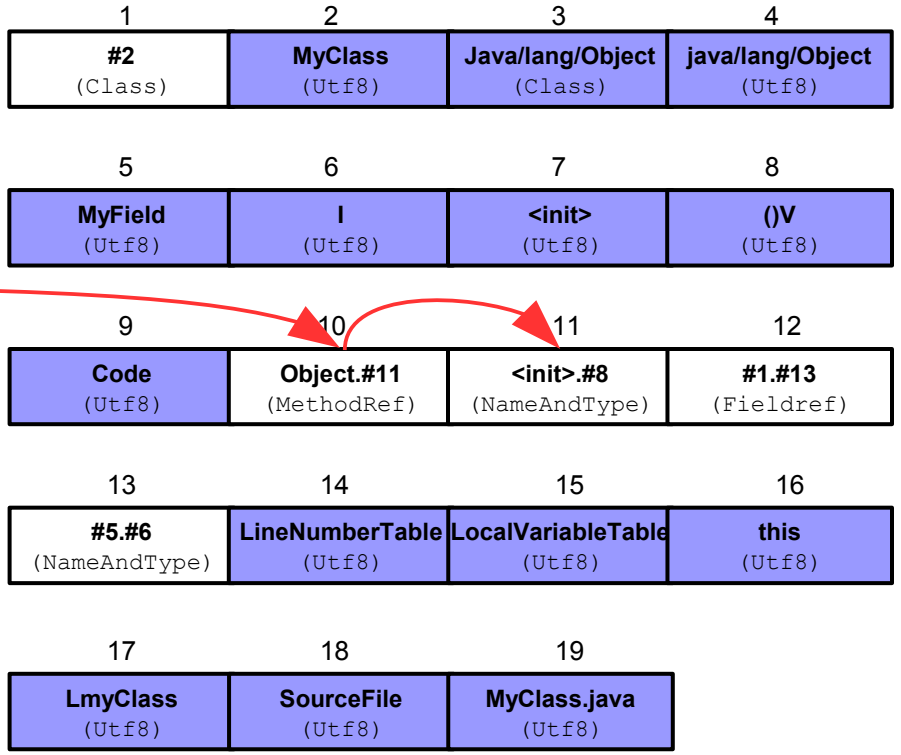

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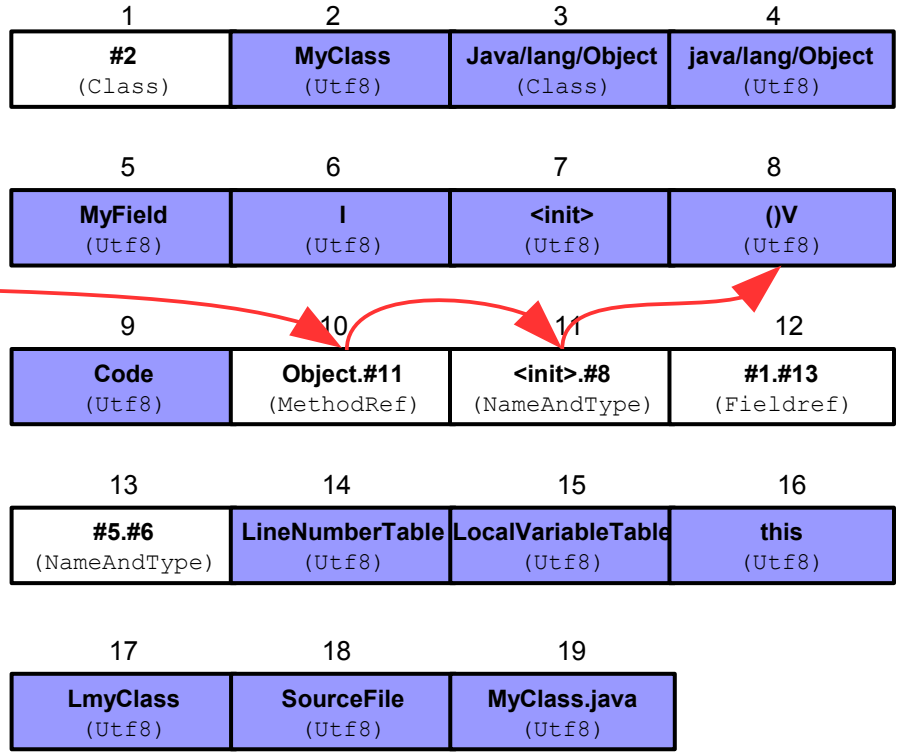

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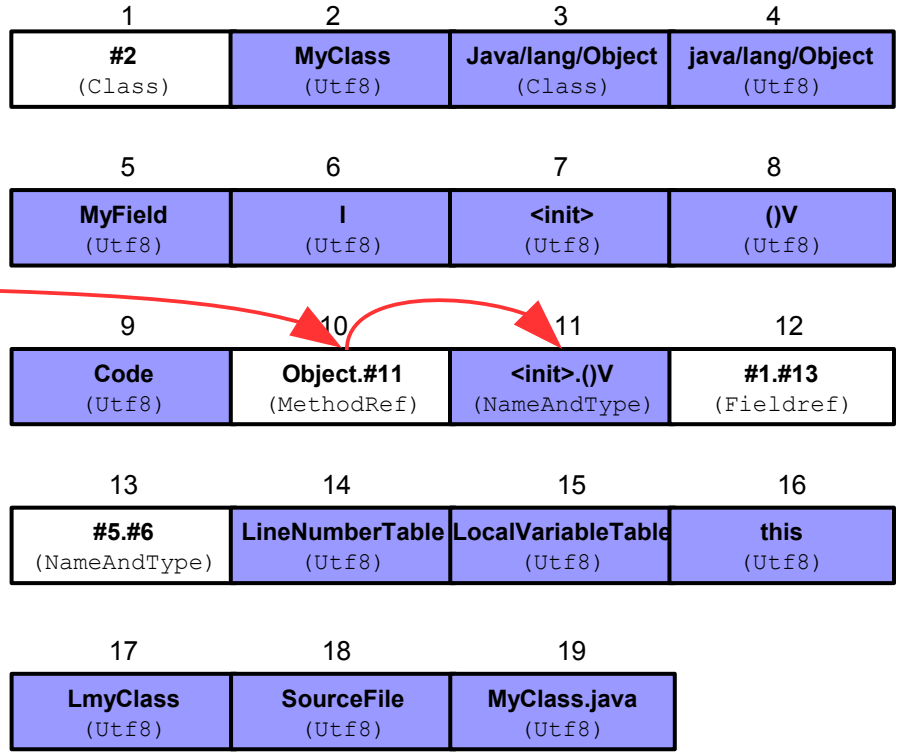

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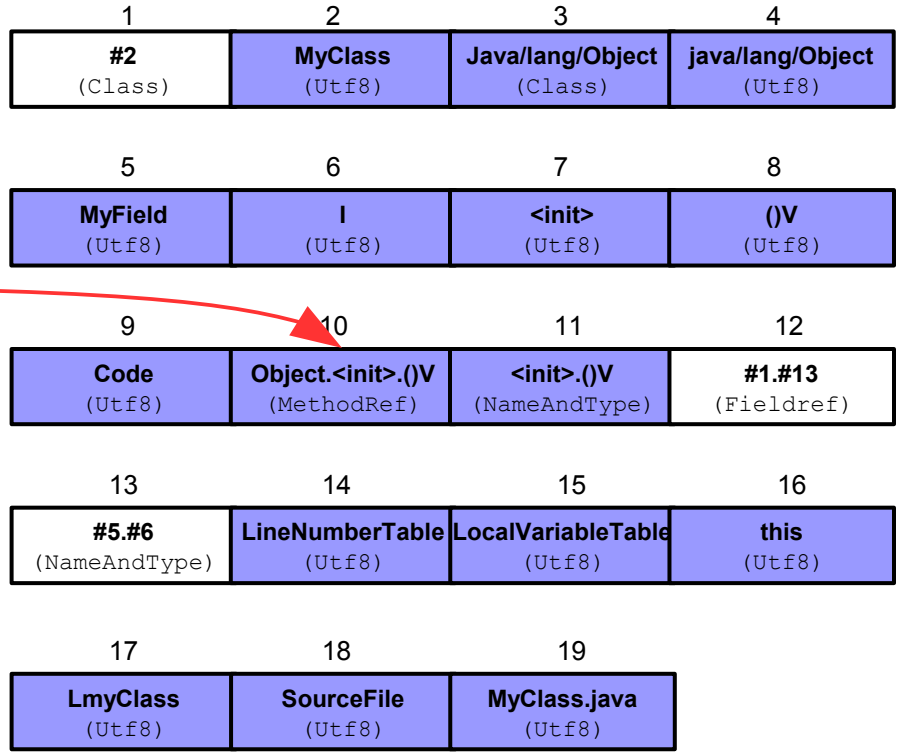

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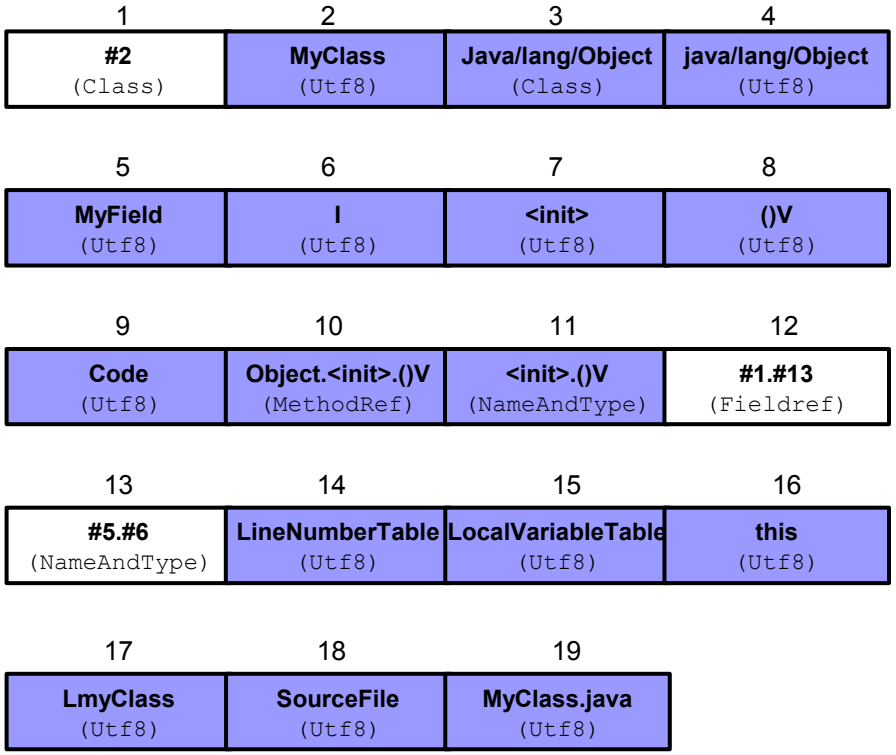

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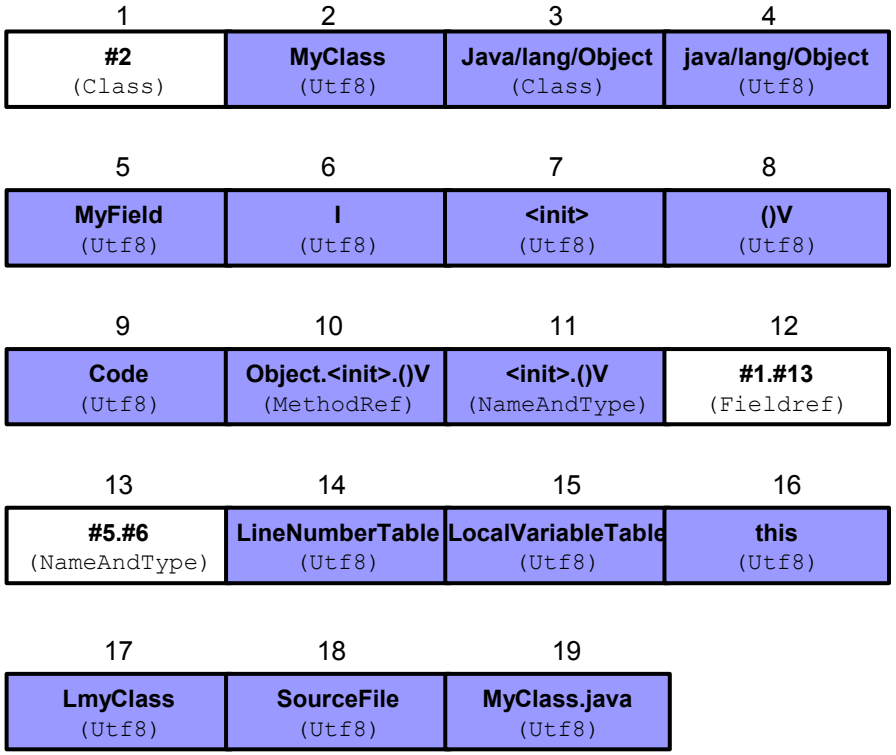

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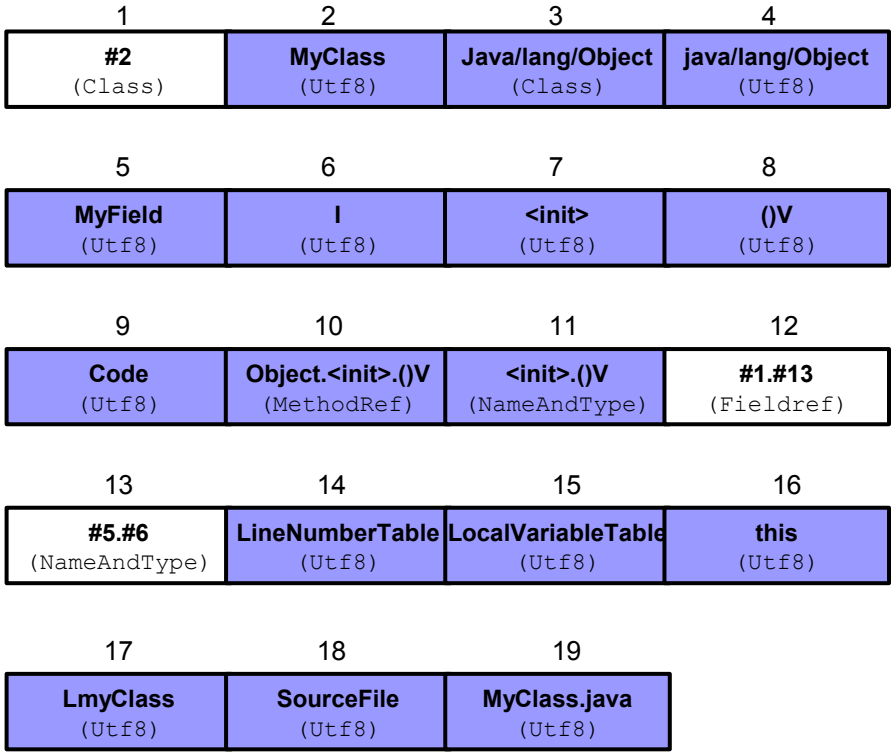

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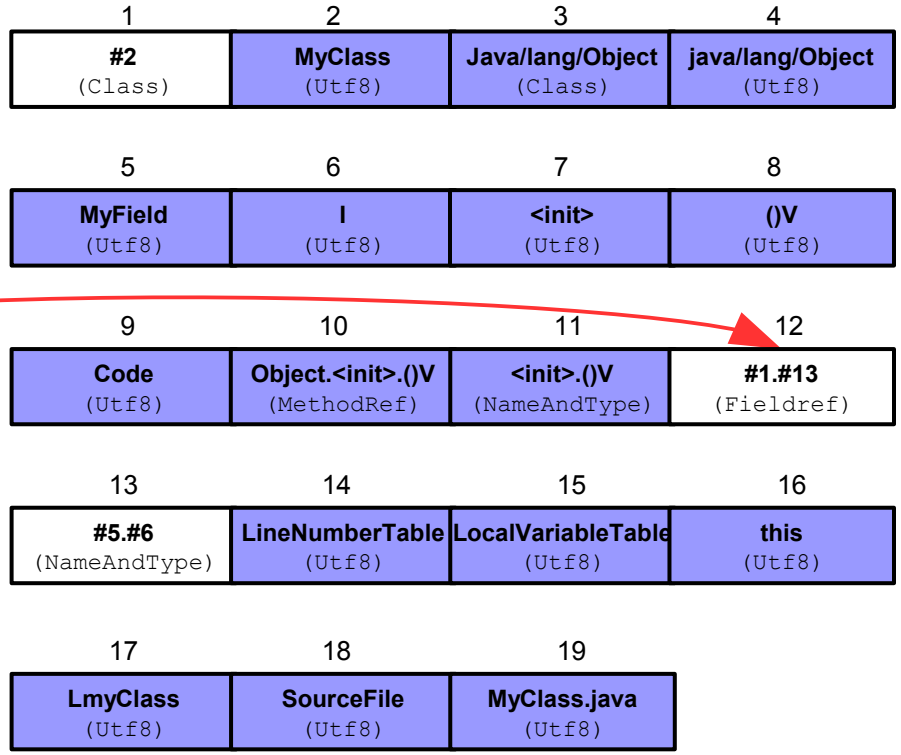

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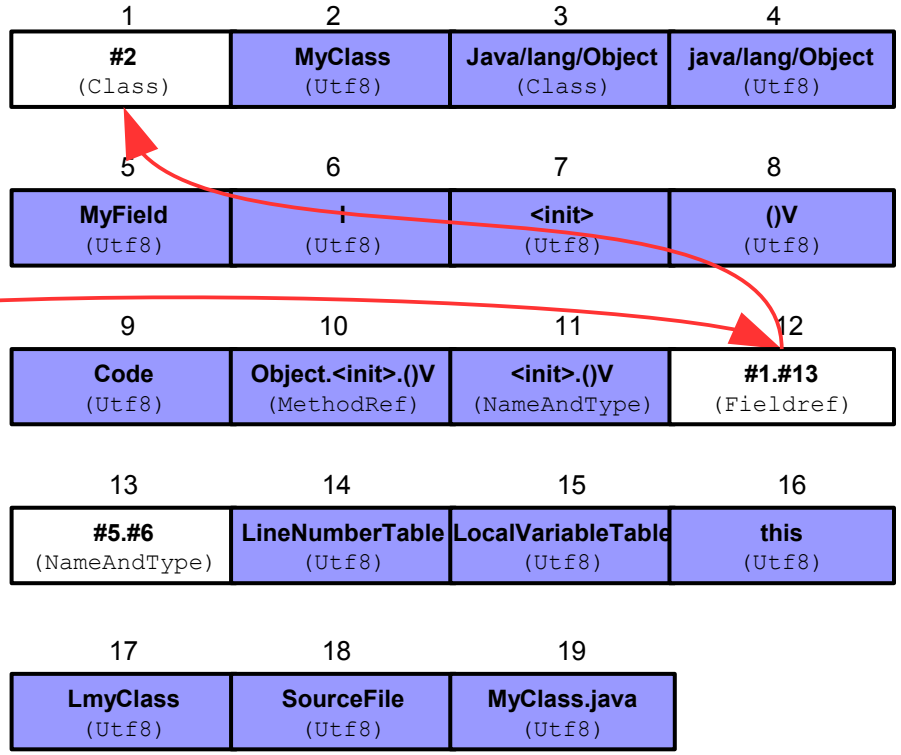

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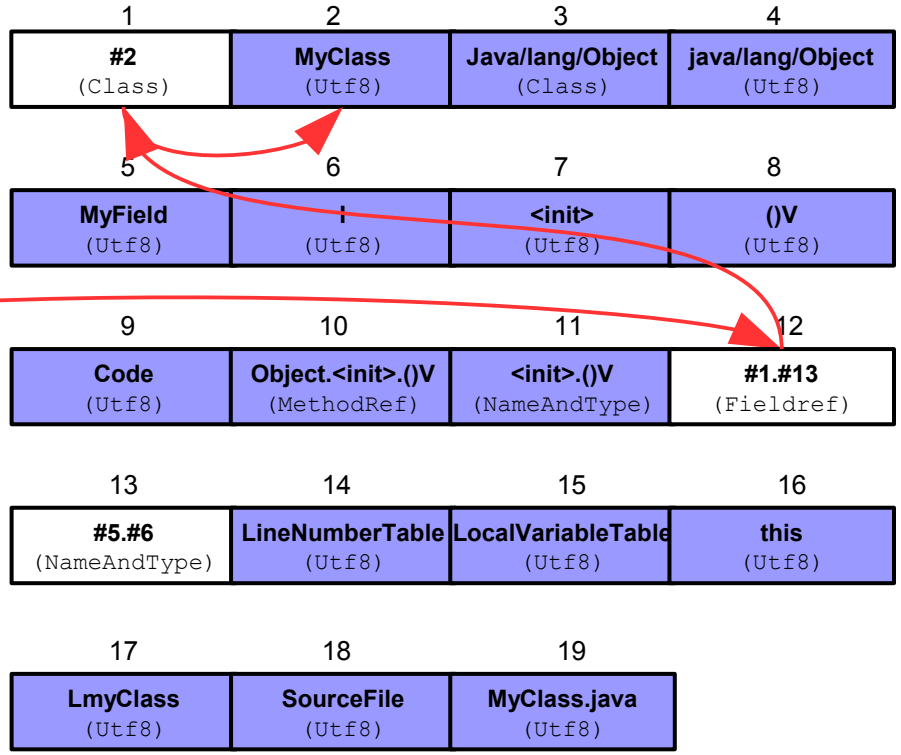

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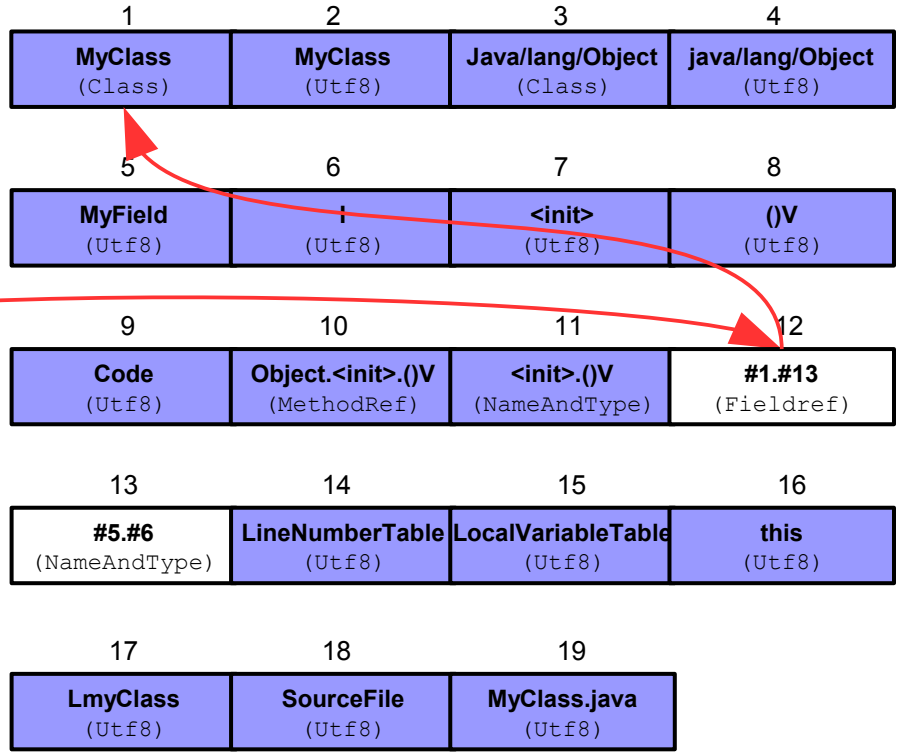

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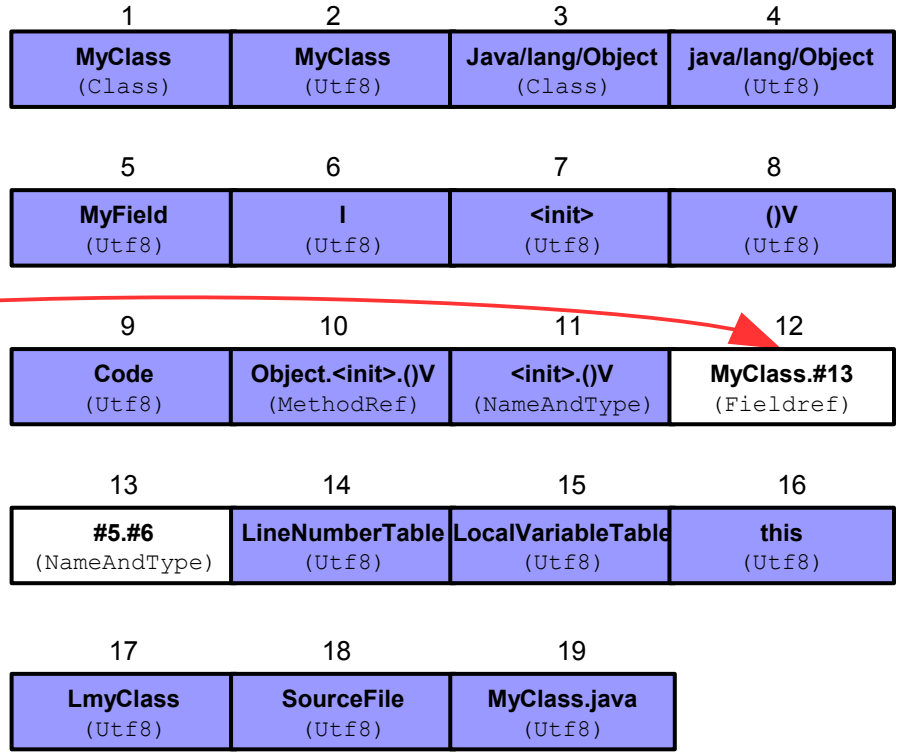

Anatomy of a Java Class File

```
public class MyClass {String[] args) {
    public int myField = 48;
}
```

```
public int myField;
  flags: ACC_PUBLIC

public MyClass();
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  Code:
  stack=2, locals=1, args_size=1
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    1: invokespecial Object.<init>.()V
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    5: bipush        48
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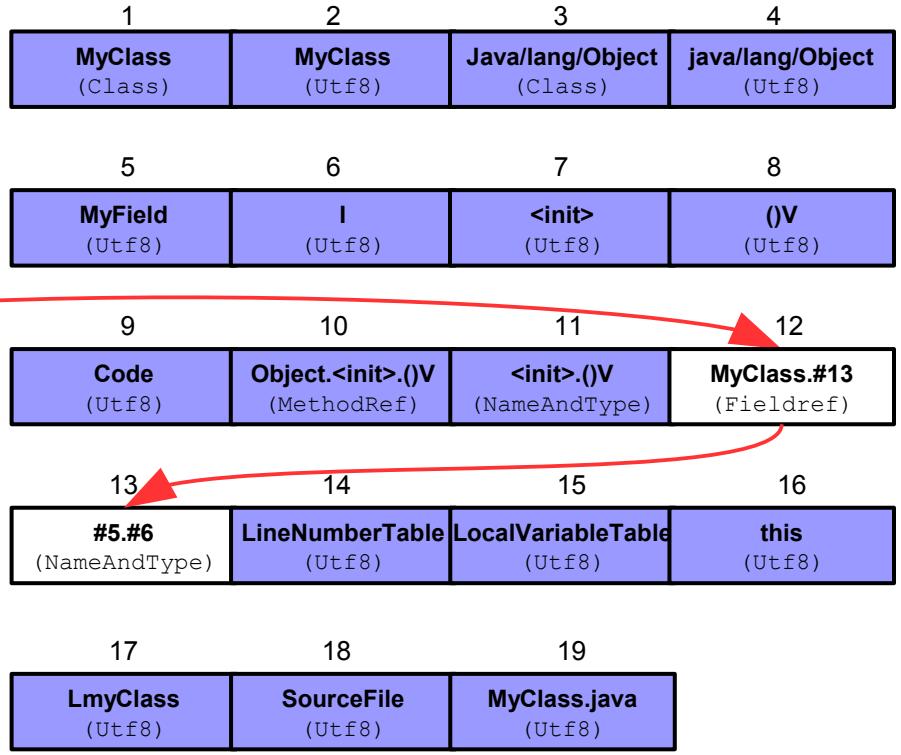

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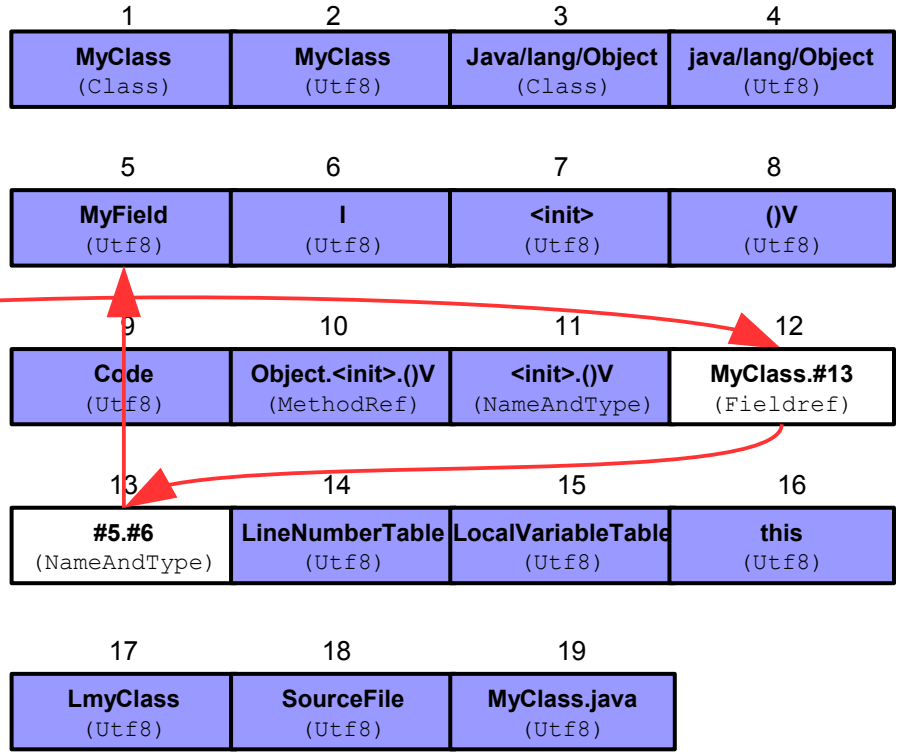

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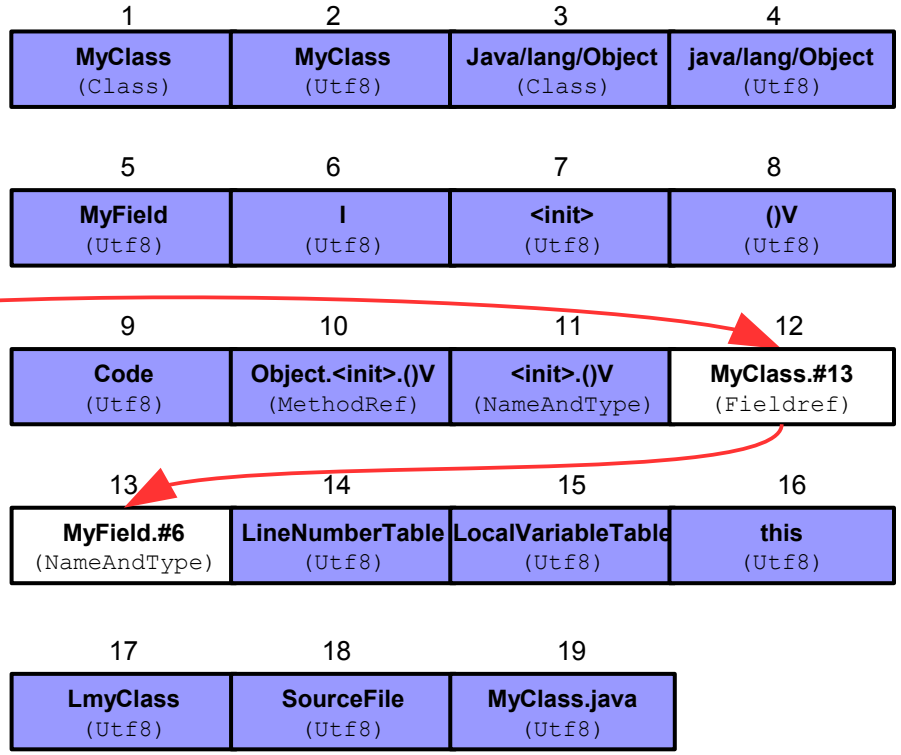

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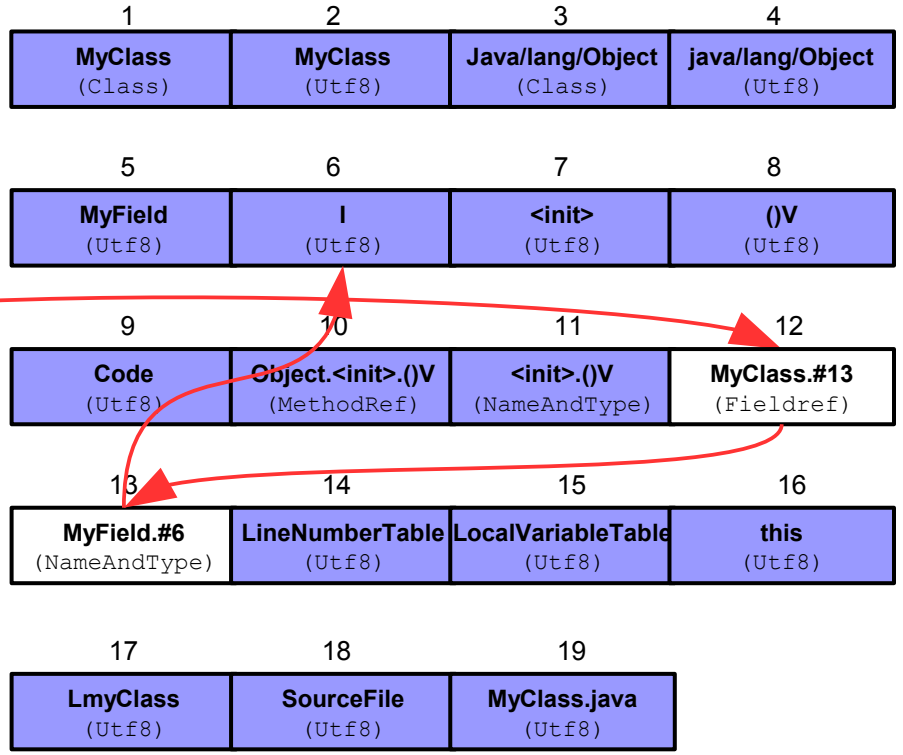

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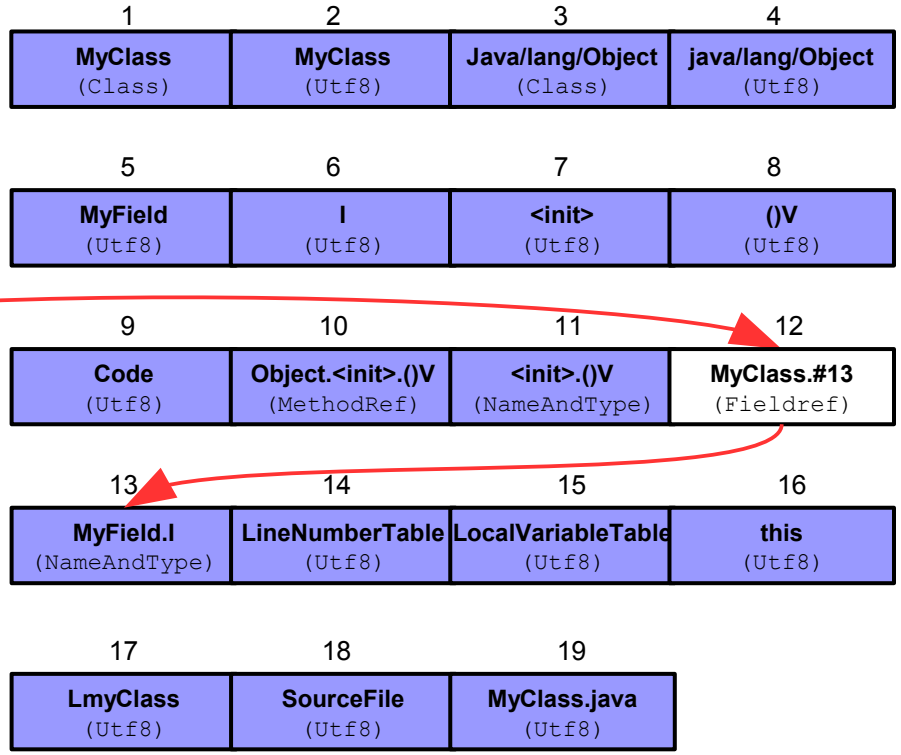

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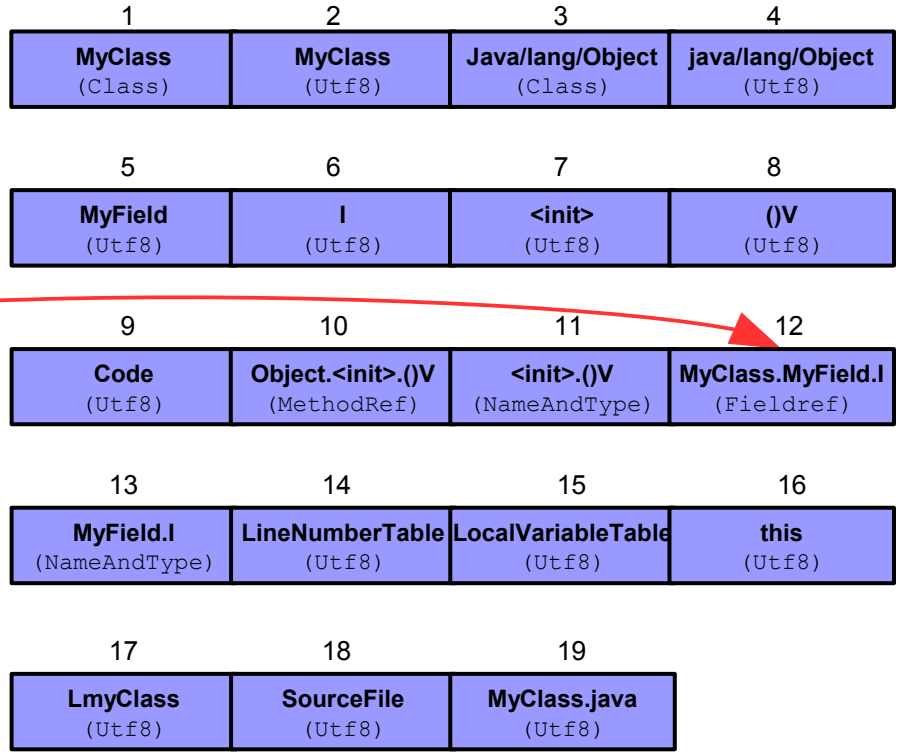

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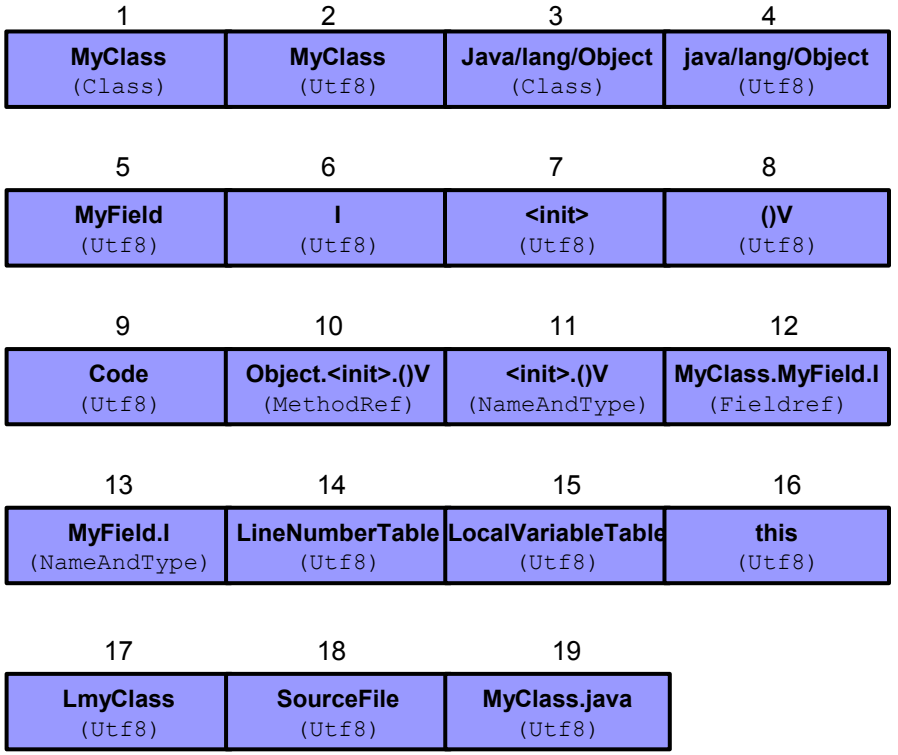

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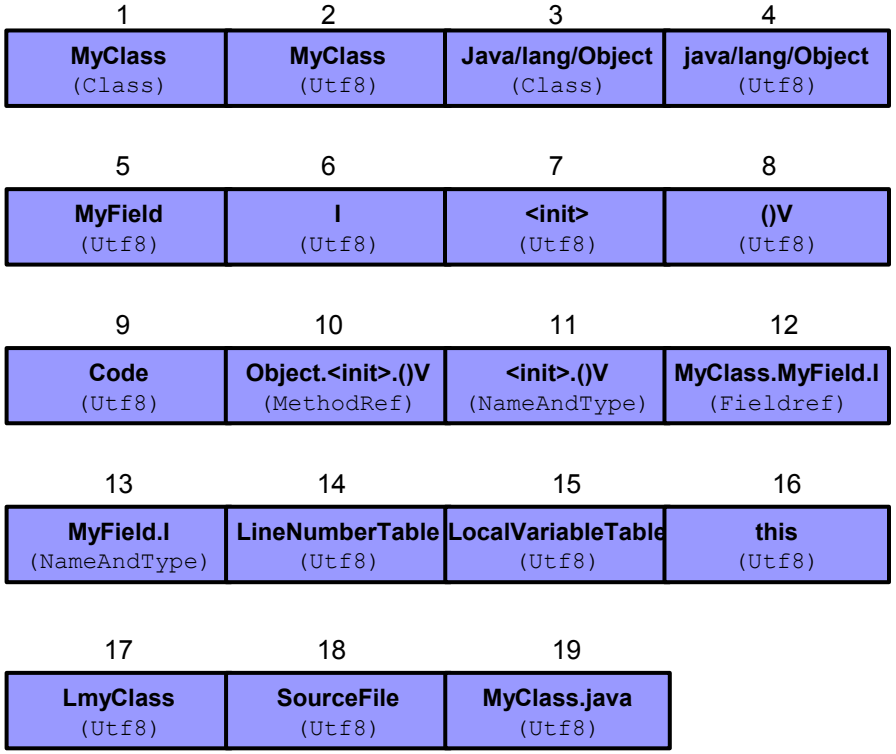

Java ByteCode Execution

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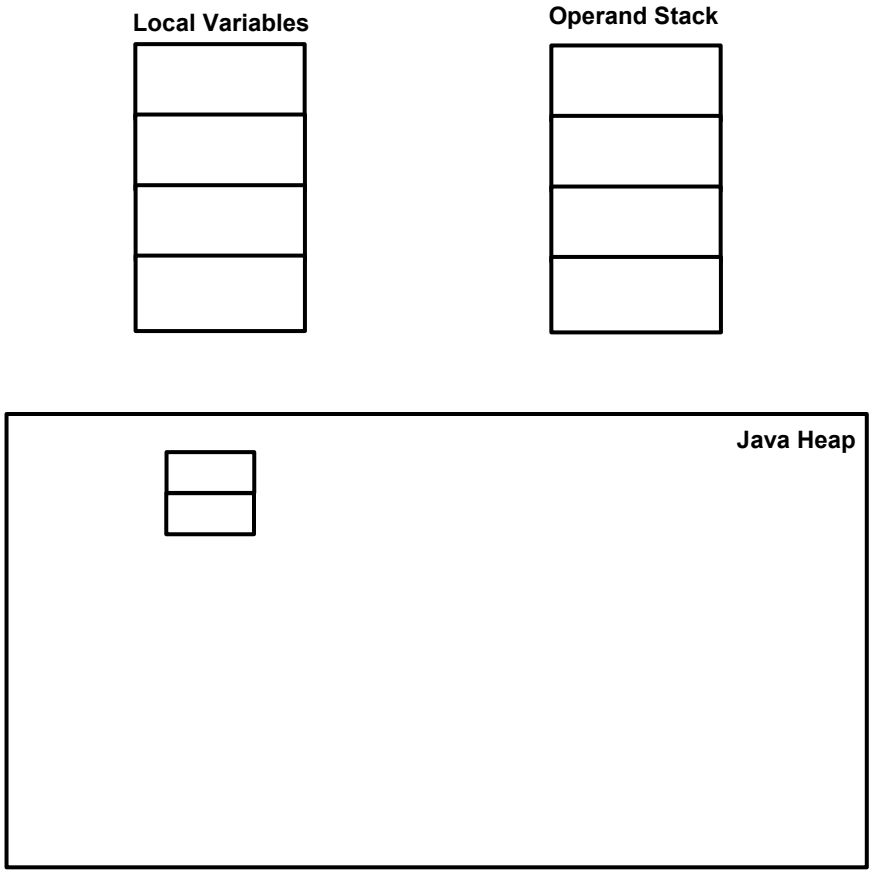

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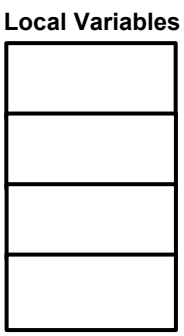

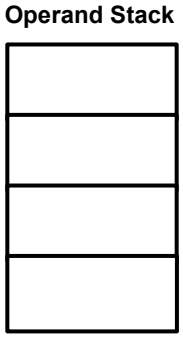

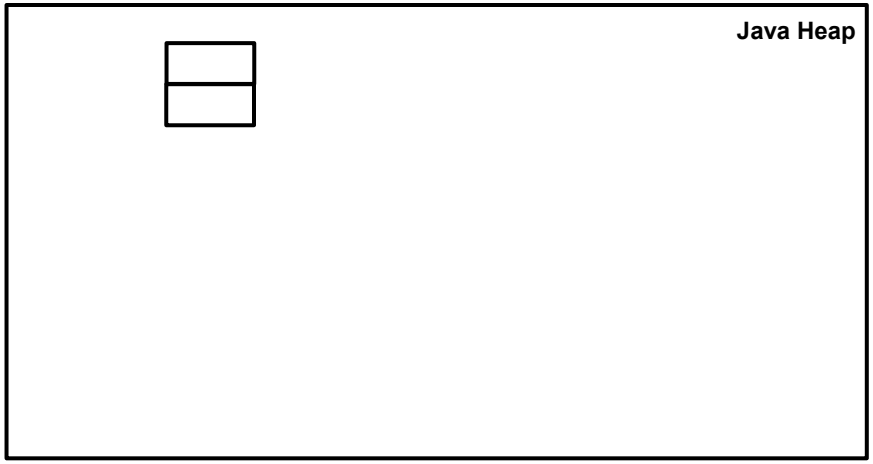

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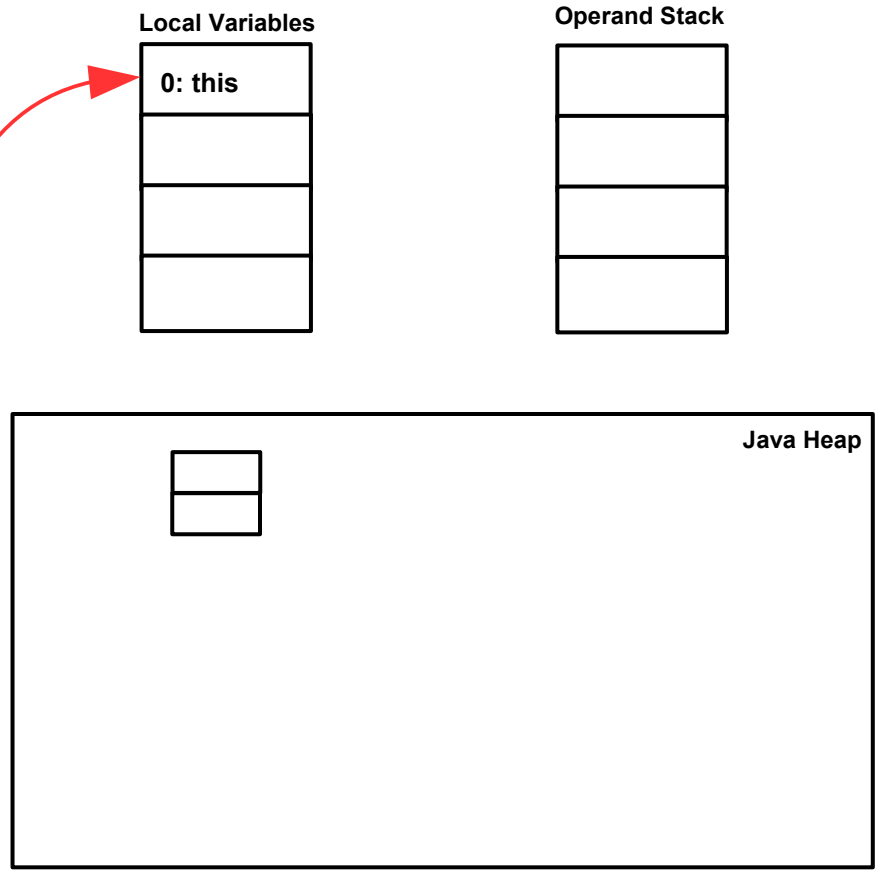

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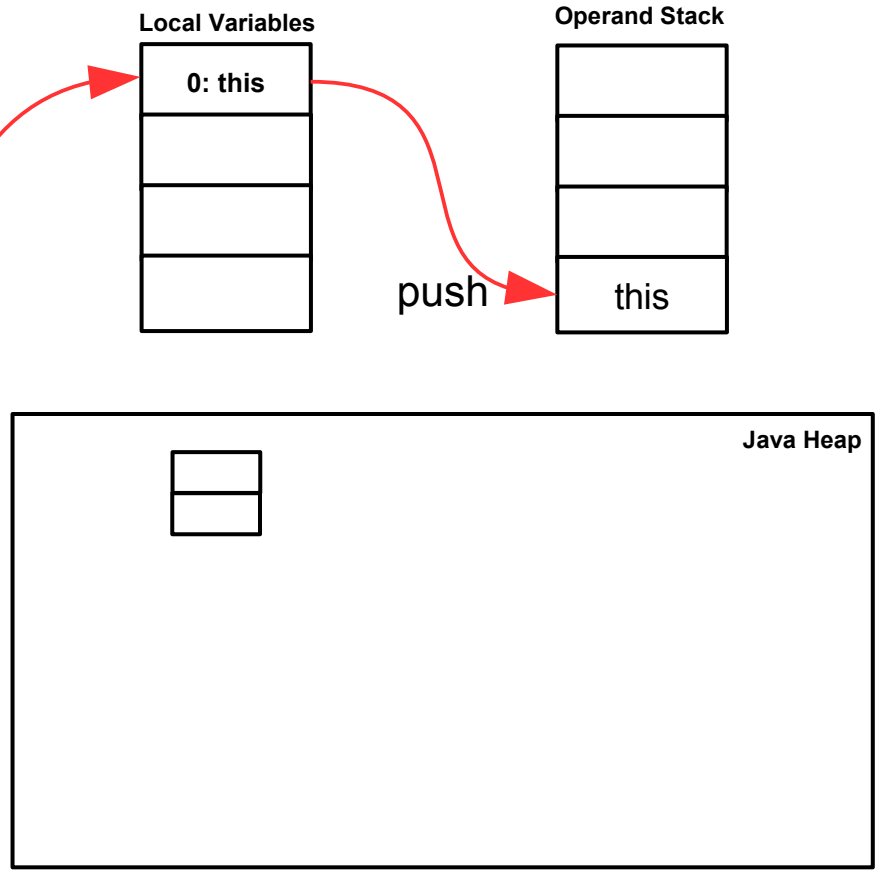

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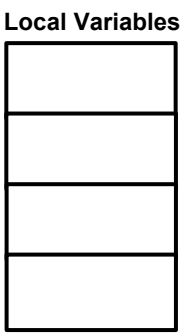

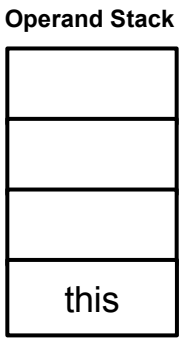

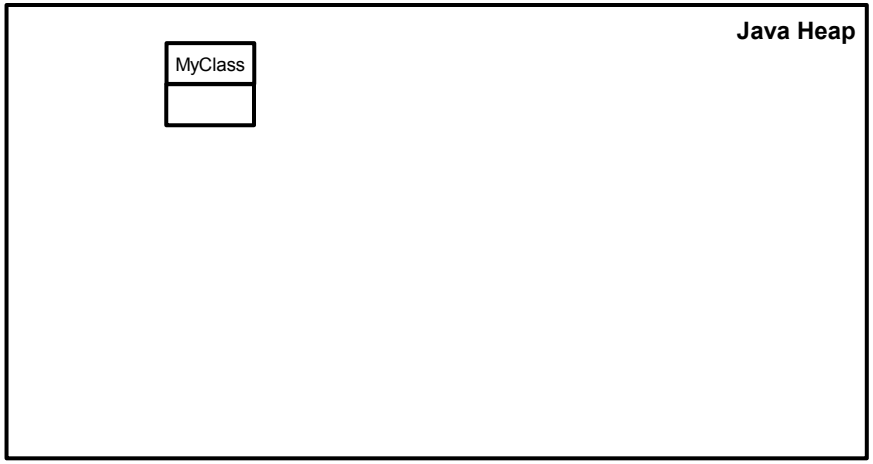

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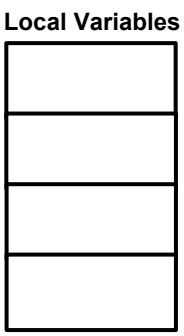

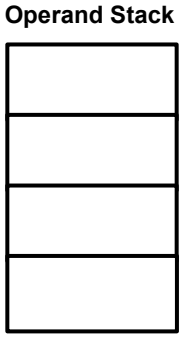

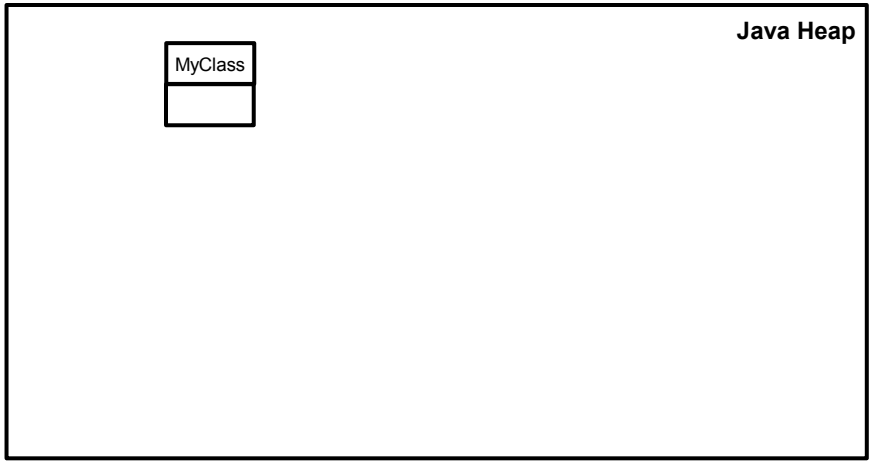

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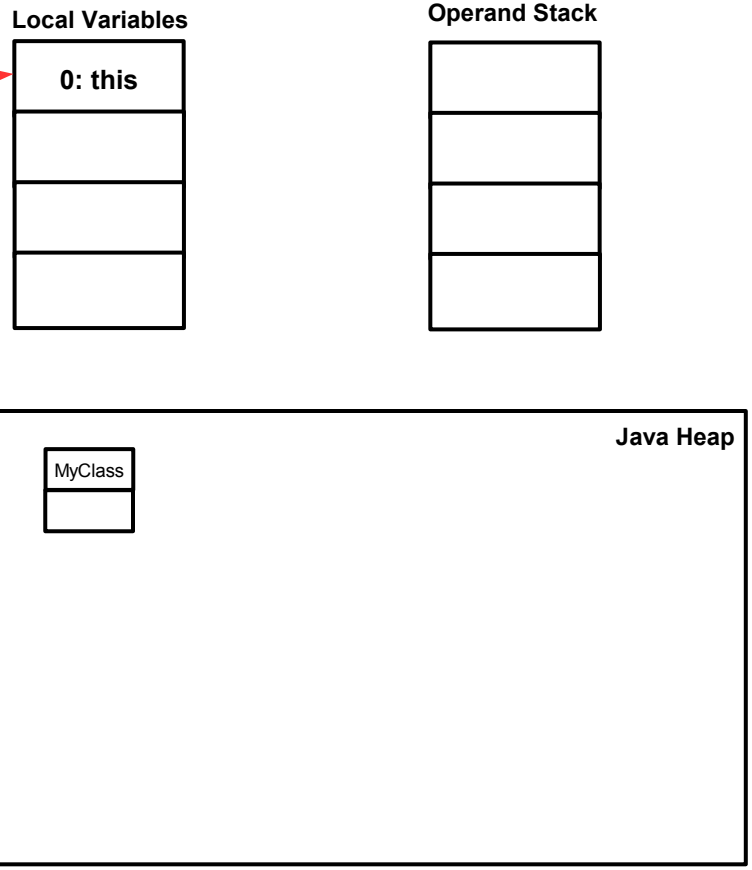

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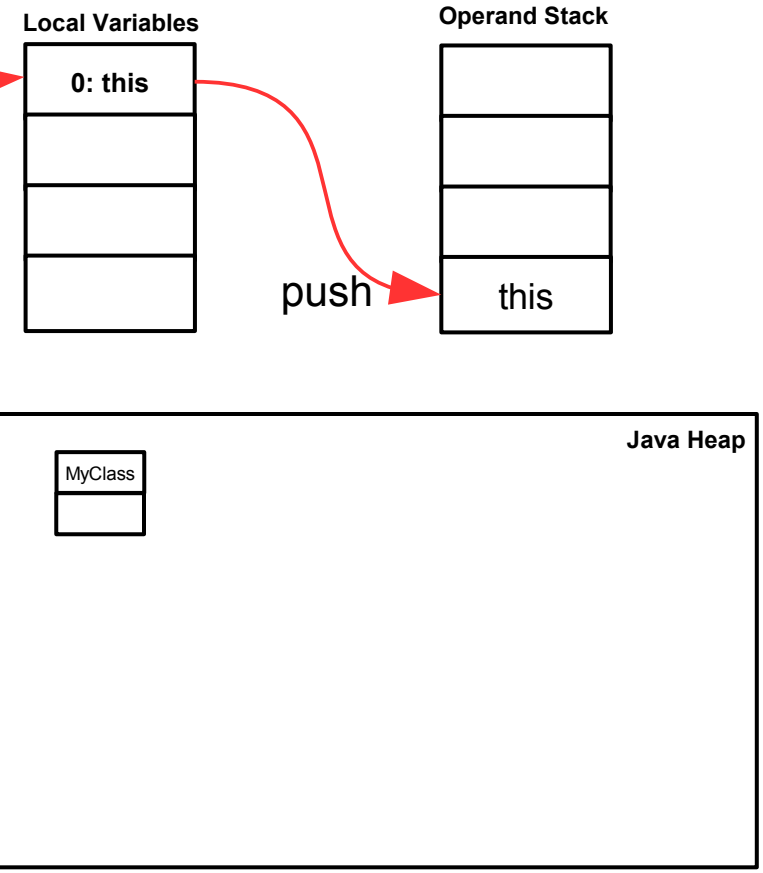

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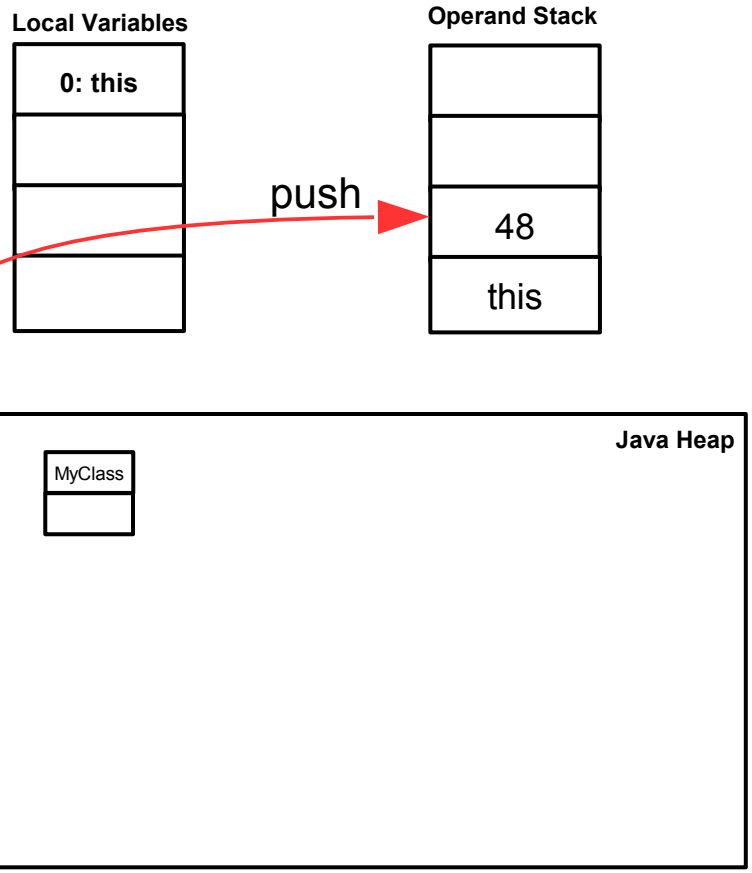

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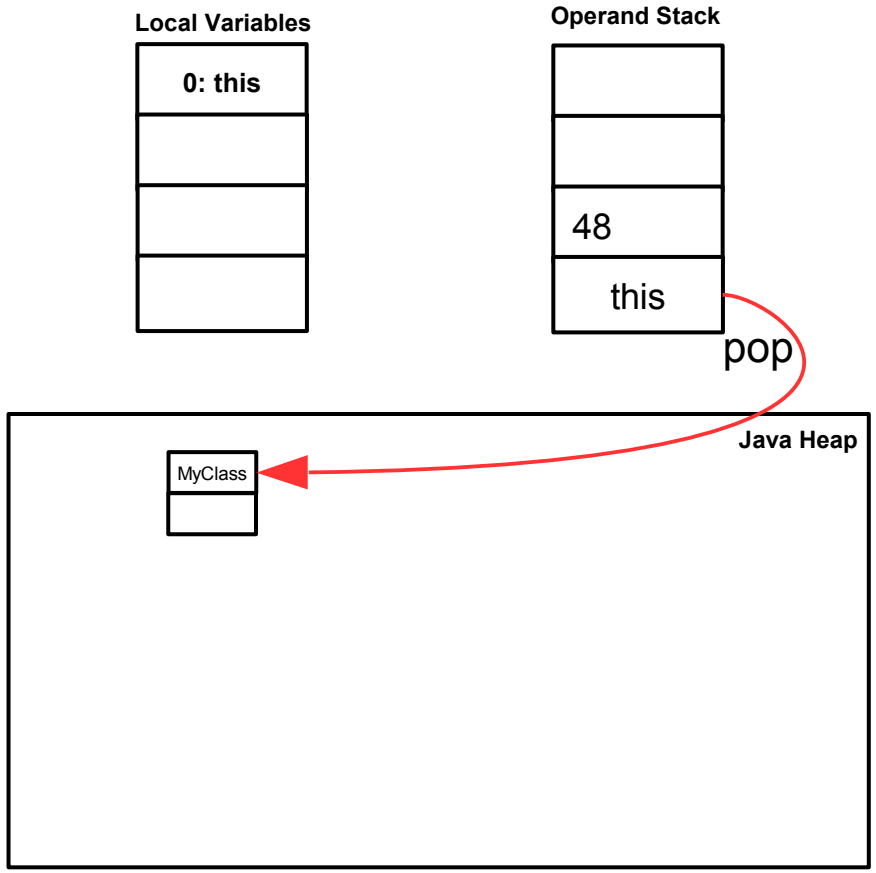

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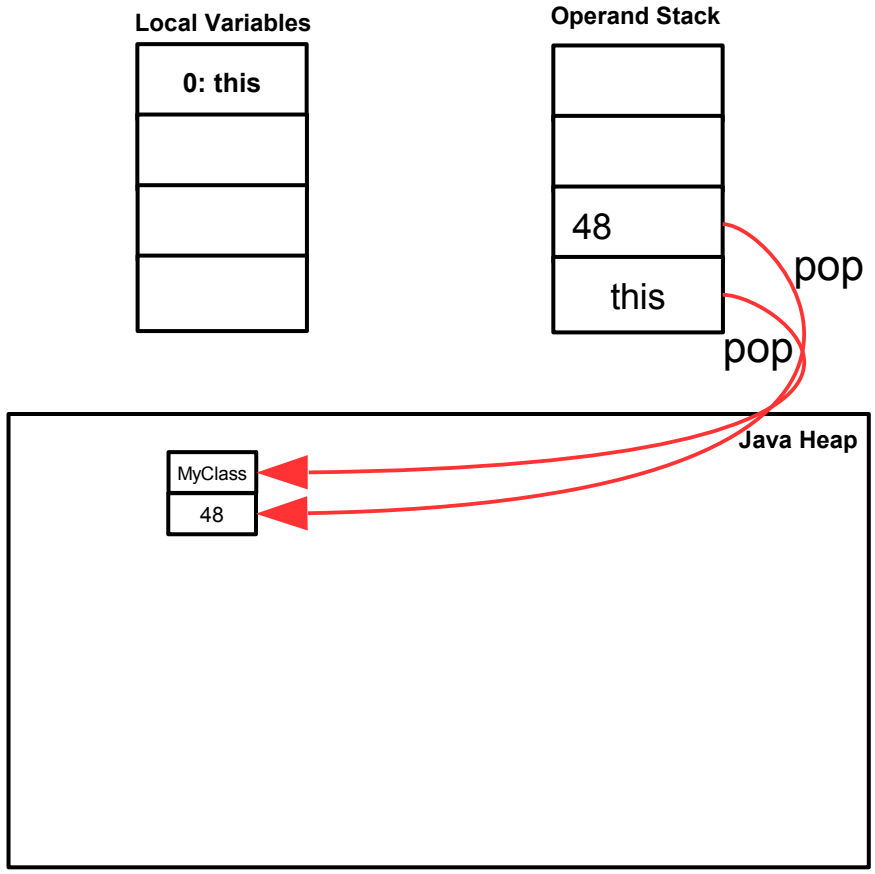

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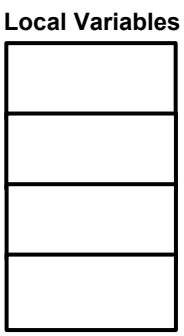

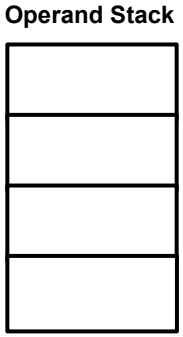

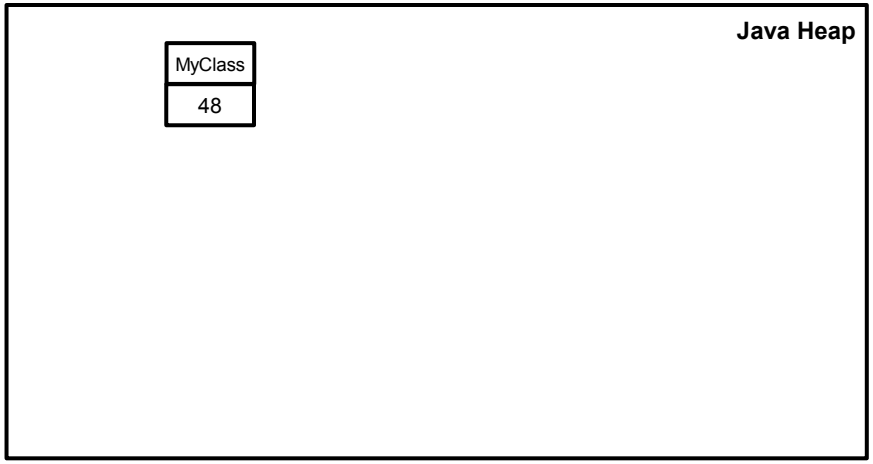

Machine Code

Executing Java Code

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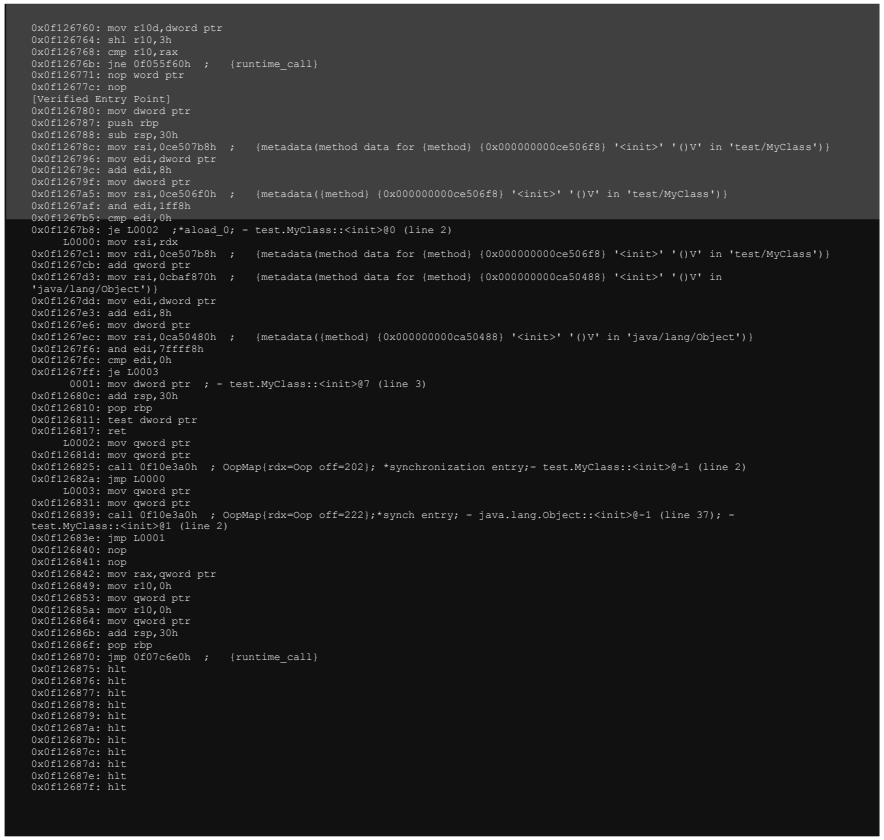

Executing Java Code

```
public class MyClass {String[] args) {
    public int myField = 48;
}
```

```
public int myField;
  flags: ACC_PUBLIC

public MyClass();
  flags: ACC_PUBLIC
 Code:
 stack=2, locals=1, args_size=1
   0: aload_0
   1: invokespecial Object.<init>.()V
   4: aload_0
   5: bipush        48
   7: putfield      MyClass.MyField.I
  10: return
 LineNumberTable:
   line 2: 0
   line 3: 4
   line 2: 10
 LocalVariableTable:
   0       11      0  this    LmyClass;
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0x0f126760: mov r10d,dword ptr
0x0f126764: shl r10,3h
0x0f126768: cmp r10,rax
0x0f12676b: jne 0f055f60h  ;   {runtime_call}
0x0f126771: nop word ptr
0x0f12677c: nop
[Verified Entry Point]
0x0f126780: mov dword ptr
0x0f126787: push rbp
0x0f126788: sub rsp,30h
0x0f12678c: mov rsi,0ce507b8h  ;   {metadata(method data for {method} {0x000000000ce506f8} '<init>' '()V' in 'test/MyClass')}
0x0f126796: mov edi,dword ptr
0x0f12679c: add edi,8h
0x0f12679f: mov dword ptr
0x0f1267a5: mov rsi,0ce506f0h  ;   {metadata({method} {0x000000000ce506f8} '<init>' '()V' in 'test/MyClass')}
0x0f1267af: and edi,1ff8h
0x0f1267b5: cmp edi,0h
0x0f1267b8: je L0002  ;*aload_0; - test.MyClass::<init>@0 (line 2)
      L0000: mov rsi,rdx
0x0f1267c1: mov rdi,0ce507b8h  ;   {metadata(method data for {method} {0x000000000ce506f8} '<init>' '()V' in 'test/MyClass')}
0x0f1267cb: add qword ptr
0x0f1267d3: mov rsi,0cbaf870h  ;   {metadata(method data for {method} {0x000000000ca50488} '<init>' '()V' in
'java/lang/Object')}
0x0f1267dd: mov edi,dword ptr
0x0f1267e3: add edi,8h
0x0f1267e6: mov dword ptr
0x0f1267ec: mov rsi,0ca50480h  ;   {metadata({method} {0x000000000ca50488} '<init>' '()V' in 'java/lang/Object')}
0x0f1267f6: and edi,7ffff8h
0x0f1267fc: cmp edi,0h
0x0f1267ff: je L0003
      0001: mov dword ptr  ; - test.MyClass::<init>@7 (line 3)
0x0f12680c: add rsp,30h
0x0f126810: pop rbp
0x0f126811: test dword ptr
0x0f126817: ret
      L0002: mov qword ptr
0x0f12681d: mov qword ptr
0x0f126825: call 0f10e3a0h  ; OopMap{rdx=Oop off=202}; *synchronization entry;- test.MyClass::<init>@-1 (line 2)
0x0f12682a: jmp L0000
      L0003: mov qword ptr
0x0f126831: mov qword ptr
0x0f126839: call 0f10e3a0h  ; OopMap{rdx=Oop off=222};*synch entry; - java.lang.Object::<init>@-1 (line 37); -
test.MyClass::<init>@1 (line 2)
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0x0f12686b: add rsp,30h
0x0f12686f: pop rbp
0x0f126870: jmp 0f07c6e0h  ;   {runtime_call}
0x0f126875: hlt
0x0f126876: hlt
0x0f126877: hlt
0x0f126878: hlt
0x0f126879: hlt
0x0f12687a: hlt
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```

Executing Java Code

```
public class MyClass {String[] args) {
    public int myField = 48;
}
```

```
public int myField;
  flags: ACC_PUBLIC

public MyClass();
  flags: ACC_PUBLIC
 Code:
 stack=2, locals=1, args_size=1
   0: aload_0
   1: invokespecial Object.<init>.()V
   4: aload_0
   5: bipush        48
   7: putfield      MyClass.MyField.I
  10: return
 LineNumberTable:
   line 2: 0
   line 3: 4
   line 2: 10
 LocalVariableTable:
   0       11      0  this    LmyClass;
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[Verified Entry Point]
0x0f126780: mov dword ptr
0x0f126787: push rbp
0x0f126788: sub rsp,30h
0x0f12678c: mov rsi,0ce507b8h  ;   {metadata(method data for {method} {0x000000000ce506f8} '<init>' '()V' in 'test/MyClass')}
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0x0f1267d3: mov rsi,0cbaf870h  ;   {metadata(method data for {method} {0x000000000ca50488} '<init>' '()V' in
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0x0f1267e3: add edi,8h
0x0f1267e6: mov dword ptr
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0x0f12686f: pop rbp
0x0f126870: jmp 0f07c6e0h  ;   {runtime_call}
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Executing Java Code

```
public class MyClass {String[] args) {
    public int myField = 48;
}
```

```
public int myField;
  flags: ACC_PUBLIC

public MyClass();
  flags: ACC_PUBLIC
 Code:
 stack=2, locals=1, args_size=1
   0: aload_0
   1: invokespecial Object.<init>.()V
   4: aload_0
   5: bipush        48
   7: putfield      MyClass.MyField.I
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 LineNumberTable:
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0x0f126780: mov dword ptr
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Executing Java Code

```
public class MyClass {String[] args) {
    public int myField = 48;
}
```

```
public int myField;
  flags: ACC_PUBLIC

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  Code:
  stack=2, locals=1, args_size=1
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    5: bipush        48
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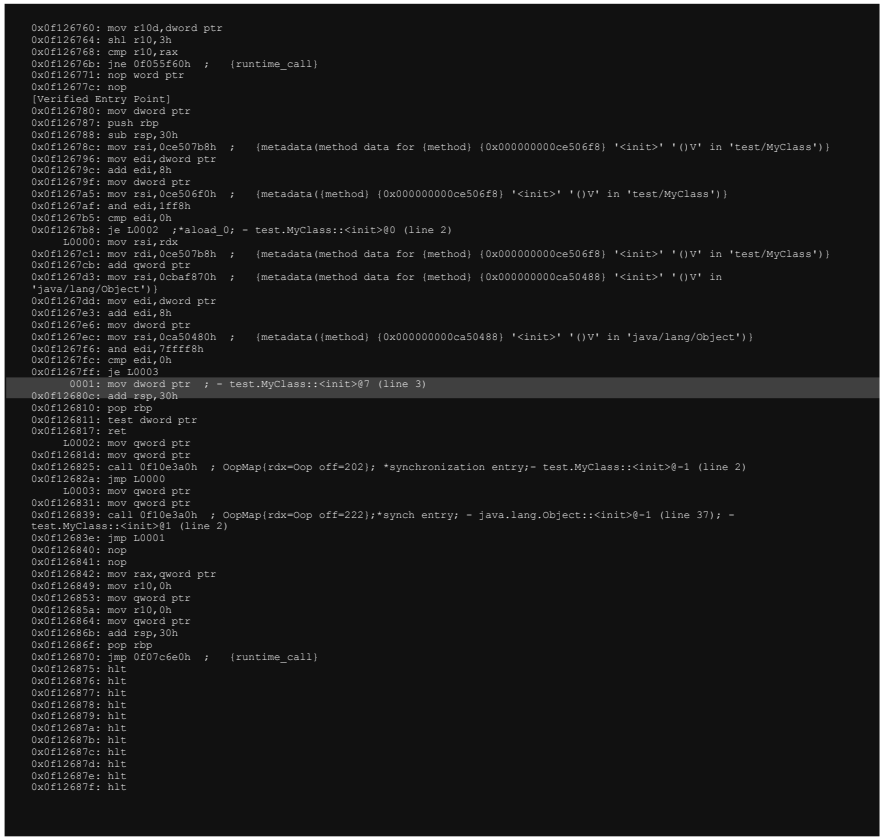

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      0001: mov dword ptr  ; - test.MyClass::<init>@7 (line 3)
0x0f12680c: add rsp,30h
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Executing Java Code

```
public class MyClass {String[] args) {
    public int myField = 48;
}
```

```
public int myField;
  flags: ACC_PUBLIC

public MyClass();
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  Code:
  stack=2, locals=1, args_size=1
    0: aload_0
    1: invokespecial Object.<init>.()V
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Executing Java Code

```
public class MyClass {String[] args) {
    public int myField = 48;
}
```

```
public int myField;
  flags: ACC_PUBLIC

public MyClass();
  flags: ACC_PUBLIC
 Code:
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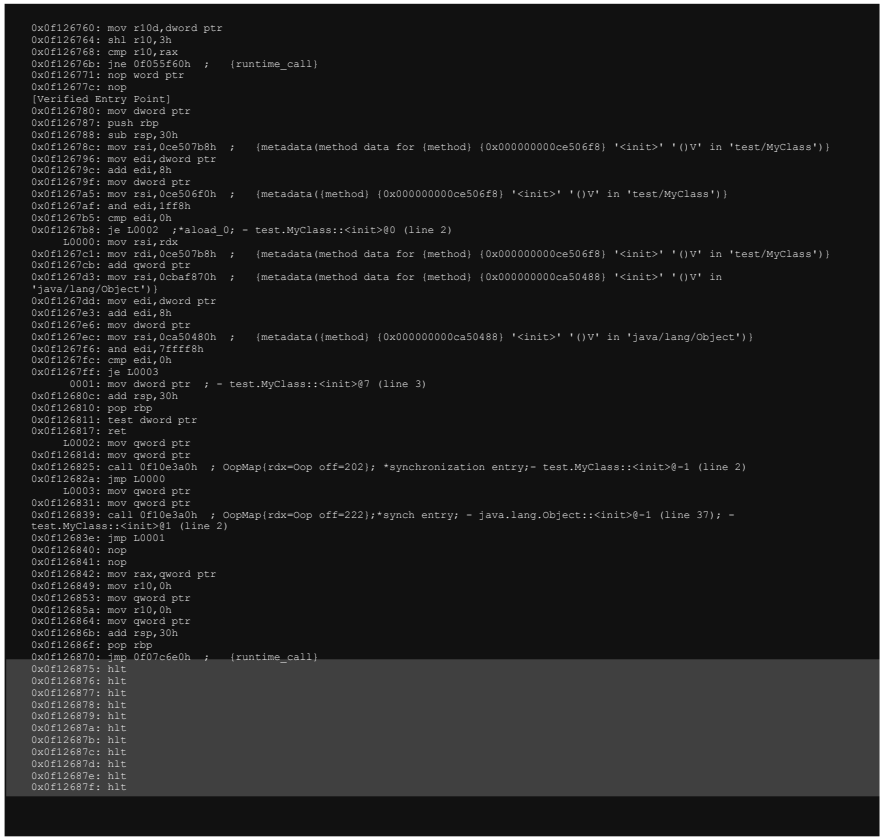


Just In Time Compilation

Bytecode optimization

```
public int[] intArr = {0, 1, 2};
```

Approach #1:

```
public synchronized int sync1(){
    return intArr[0];
}
```

5 bytecodes

```
0: aload_0
1: getfield      #12
4: iconst_0
5: iaload
6: ireturn
```

Approach #2:

```
public int sync2(){
   synchronized (this){
       return intArr[0];
   }
}
```

14 bytecodes

```
 0: aload_0
 1: dup
 2: astore_1
 3: monitorenter
 4: aload_0
 5: getfield      #12
 8: iconst_0
 9: iaload
10: aload_1
11: monitorexit
12: ireturn
13: aload_1
14: monitorexit
15: athrow
```

Which is faster?

- A: approach #1
- B: approach #2

Bytecode optimization

```
public int[] intArr = {0, 1, 2};
```

Approach #1:

```
public synchronized int sync1(){
    return intArr[0];
}
```

5 bytecodes

```
0: aload_0
1: getfield      #12
4: iconst_0
5: iaload
6: ireturn
```

Approach #2:

```
public int sync2(){
   synchronized (this){
       return intArr[0];
   }
}
```

14 bytecodes

```
 0: aload_0
 1: dup
 2: astore_1
 3: monitorenter
 4: aload_0
 5: getfield      #12
 8: iconst_0
 9: iaload
10: aload_1
11: monitorexit
12: ireturn
13: aload_1
14: monitorexit
15: athrow
```

Which is faster?

- A: approach #1
- B: approach #2

Answer: C – they're both the same

Inlining

Inlining

```
public static int factorial(int num) {
    int factorial = 1;
    for (int i = 1; i <= num; i++) {
        factorial = multiply(factorial, i);
    }
    return factorial;
}


public static int multiply(int a, int b){
    return a * b;
}
```

Inlining

```
public static int factorial(int num) {
    int factorial = 1;
    for (int i = 1; i <= num; i++) {
        factorial = multiply(factorial, i);
    }
    return factorial;
}
```

67 instructions

```
public static int multiply(int a, int b){
    return a * b;
}
```

Inlining

```
public static int factorial(int num) {
    int factorial = 1;
    for (int i = 1; i <= num; i++) {
        factorial = multiply(factorial, i);
    }
    return factorial;
}
```

67 instructions

```
public static int multiply(int a, int b){
    return a * b;
}
```

9 instructions

Inlining

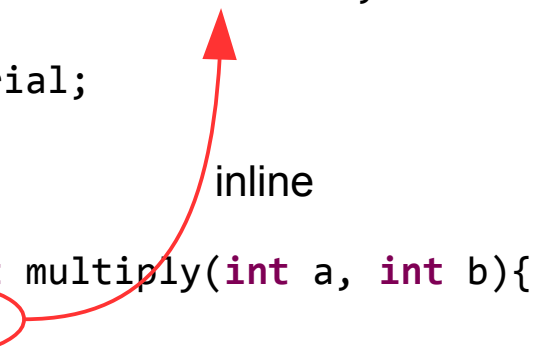
```
public static int factorial(int num) {
    int factorial = 1;
    for (int i = 1; i <= num; i++) {
        factorial =
    }
    return factorial;
}


public static int multiply(int a, int b){
    return a * b;
}
```

Inlining

```
public static int factorial(int num) {
    int factorial = 1;
    for (int i = 1; i <= num; i++) {
        factorial = factorial * i;
    }
    return factorial;
}

public static int multiply(int a, int b){
    return a * b;
}
```



Inlining

```
public static int factorial(int num) {
    int factorial = 1;
    for (int i = 1; i <= num; i++) {
        factorial = factorial * i;
    }
    return factorial;
}
```

71 instructions

```
public static int multiply(int a, int b){
    return a * b;
}
```

Inlining

```
public static int factorial(int num) {
    int factorial = 1;
    for (int i = 1; i <= num; i++) {
        factorial = factorial * i;
    }
    return factorial;
}
```

71 instructions

```
public static int multiply(int a, int b){
    return a * b;
}
```

9 instructions

Inlining

```
public static int factorial(int num) {
    int factorial = 1;
    for (int i = 1; i <= num; i++) {
        factorial = factorial * i;
    }
    return factorial;
}
```

71 instructions

```
public static int multiply(int a, int b){
    return a * b;
}
```

9 instructions

5 instructions saved per iteration

Loop Unrolling

```
private static final String[] numbers = {"0", "1", "2", "3", "4"};

public static int total() {
    int result = 0;

    for (String num : numbers) {
        result += parse(num);
    }
    return result;
}
```

28 instructions
14 on loop

```
private static int parse(String num) {
    return Integer.parseInt(num);
}
```

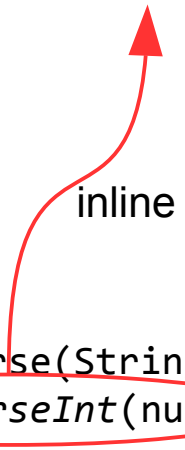
13 instructions

Loop Unrolling

```
private static final String[] numbers = {"0", "1", "2", "3", "4"};

public static int total() {
    int result = 0;

    for (String num : numbers) {
        result += Integer.parseInt(num);
    }
    return result;
}
```




```
private static int parse(String num) {
    return Integer.parseInt(num);
}
```

- Inlining removes the cost of calling *parse*

Loop Unrolling

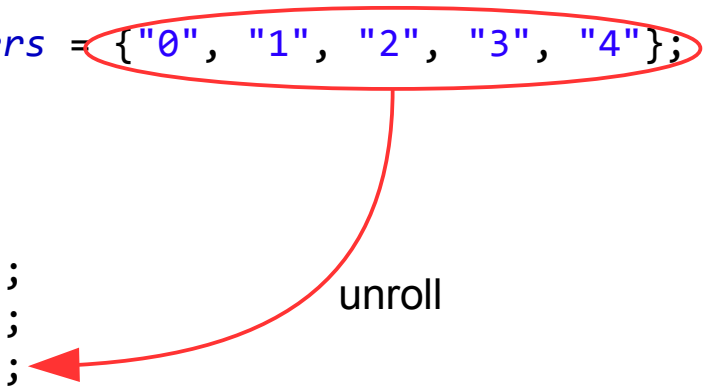
```
private static final String[] numbers = {"0", "1", "2", "3", "4"};

public static int total() {
    int result = 0;

    result += Integer.parseInt("0");
    result += Integer.parseInt("1");
    result += Integer.parseInt("2");
    result += Integer.parseInt("3");
    result += Integer.parseInt("4");

    return result;
}

private static int parse(String num) {
    return Integer.parseInt(num);
}
```



- Inlining removes the cost of calling *parse*
- Unrolling removes the cost of loop iteration

Loop Unrolling

```
private static final String[] numbers = {"0", "1", "2", "3", "4"};

public static int total() {
    int result = 0;

    result += Integer.parseInt("0");
    result += Integer.parseInt("1");
    result += Integer.parseInt("2");
    result += Integer.parseInt("3");
    result += Integer.parseInt("4");

    return result;
}

private static int parse(String num) {
    return Integer.parseInt(num);
}
```

Unrolling possible because collection is **final**

- Inlining removes the cost of calling *parse*
- Unrolling removes the cost of loop iteration

Synchronization

Synchronization approaches

```
public int[] intArr = {0, 1, 2};
```

```
public synchronized int sync1(){
    return intArr[0];
}
```

```
public int sync2(){
   synchronized (this){
       return intArr[0];
   }
}
```

- Unnecessary bytecodes removed

Lock Coarsening

```
public int[] intArr = {0, 1, 2};

public int arrayCount() {
    int result = 0;

    for (int i = 0; i < intArr.length; i++) {
        result += getEntry(i);
    }

    return result;
}

public synchronized int getEntry(int entry){
    return intArr[entry];
}
```

Lock Coarsening

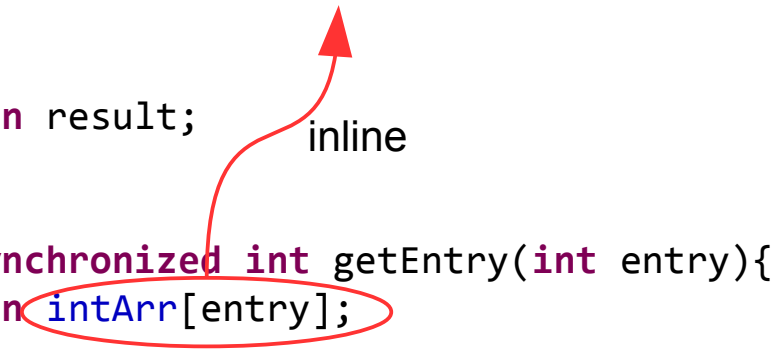
```
public int[] intArr = {0, 1, 2};

public int arrayCount() {
    int result = 0;

    for (int i = 0; i < intArr.length; i++) {
        result += intArr[entry];
    }

    return result;
}

public synchronized int getEntry(int entry){
    return intArr[entry];
}
```

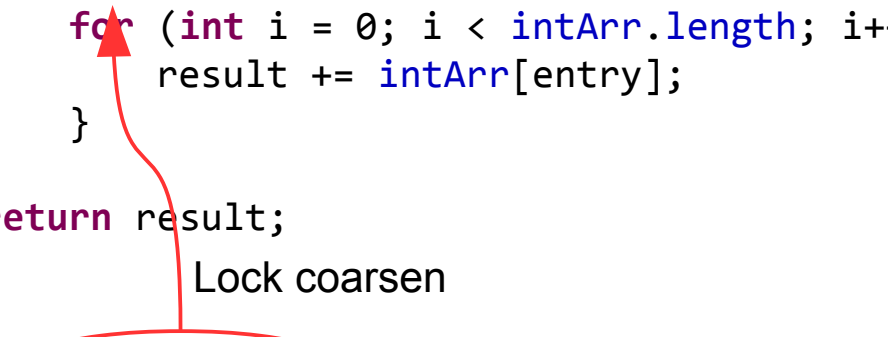


Lock Coarsening

```
public int[] intArr = {0, 1, 2};

public int arrayCount() {
    int result = 0;
    synchronized {
        for (int i = 0; i < intArr.length; i++) {
            result += intArr[entry];
        }
    }
    return result;
}

public synchronized int getEntry(int entry){
    return intArr[entry];
}
```

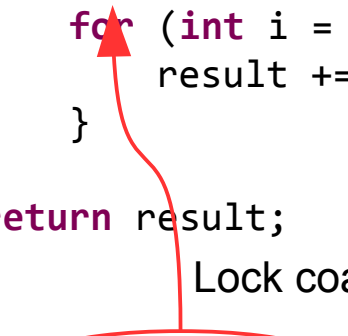


Lock Coarsening

```
public int[] intArr = {0, 1, 2};

public int arrayCount() {
    int result = 0;
    synchronized {
        for (int i = 0; i < intArr.length; i++) {
            result += intArr[entry];
        }
    }
    return result;
}

public synchronized int getEntry(int entry){
    return intArr[entry];
}
```



- Repeated locking removed

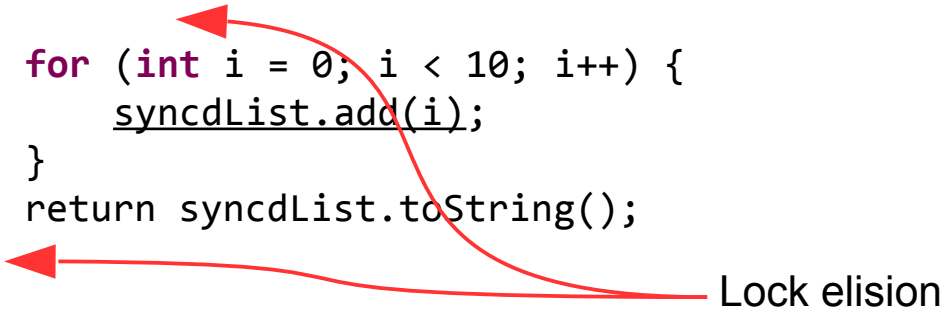
Lock Elision

```
public String walkLockedList() {
    List syncdList = new ArrayList();
    synchronized (syncdList) {
        for (int i = 0; i < 10; i++) {
            syncdList.add(i);
        }
        return syncdList.toString();
    }
}
```

Lock Elision

```
public String walkLockedList() {
    List syncdList = new ArrayList();

        for (int i = 0; i < 10; i++) {
            syncdList.add(i);
        }
        return syncdList.toString();
}
```



- Lock removed as un-necessary

Field Access

Accessing Fields: Static Fields

```
public static int test = 10;
public static int getTest() {
    return test;
}
```

30 instructions

```
private static int test = 10;
public static int getTest() {
    return test;
}
```

30 instructions

```
public final static int test = 10;
public static int getTest() {
    return test;
}
```

17 instructions

Accessing Fields: Instance Fields

```
public int test = 10;
public int getTest() {
    return test;
}
```

23 instructions

```
private int test = 10;
public int getTest() {
    return test;
}
```

23 instructions

```
public final int test = 10;
public int getTest() {
    return test;
}
```

17 instructions

Enabling Optimizations

Certainty

- Locals are faster than globals
  - Fields and statics slow; parameters and locals fast
- Constants are faster than variables
  - `final` is your friend
- `private` can be faster than `public`
  - `protected` and `package` are always just as slow as `public`
- Small methods (≤100 bytecodes) are good
- Simple is faster than complex

Analyzing the JIT

Digging into the generated assembler

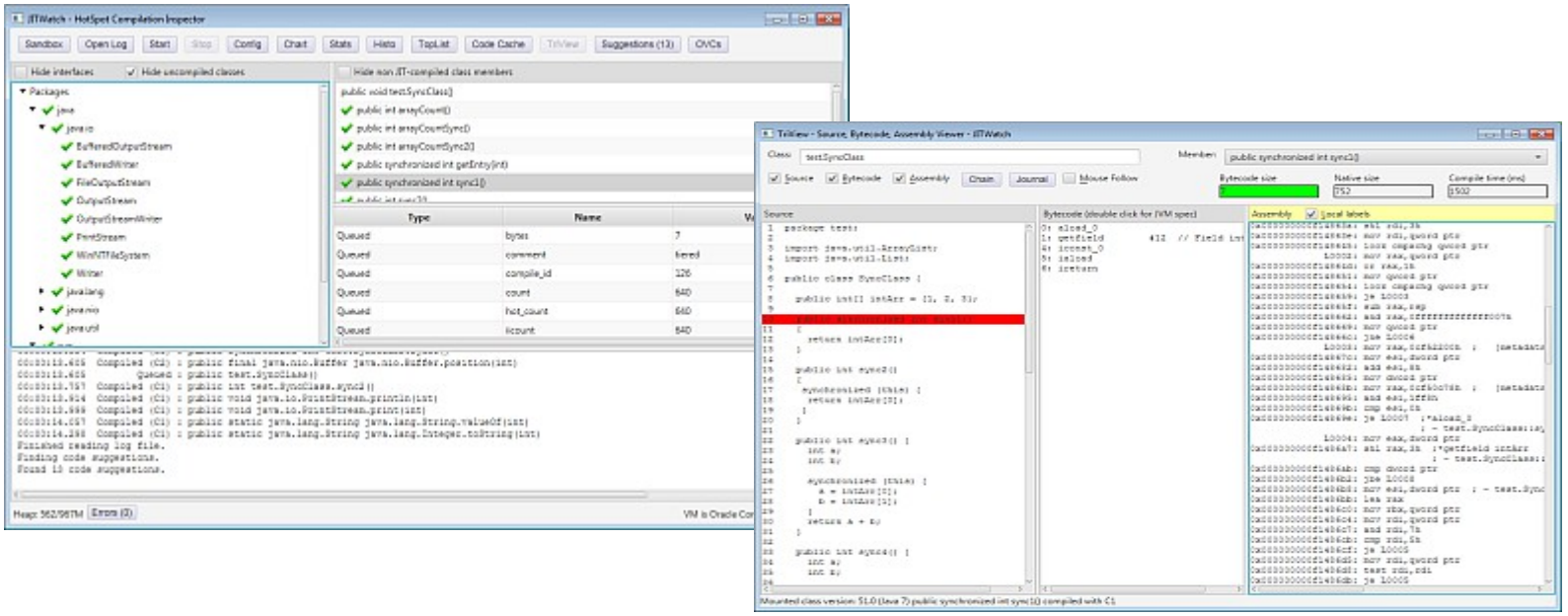
- HotSpot JIT provides options to look at JIT behaviour:
  - `-XX:+UnlockDiagnosticVMOptions`
  - `-XX:+TraceClassLoading`
  - `-XX:+LogCompilation`
  - `-XX:+PrintAssembly`

- -XX:+PrintAssembly requires additional `hdis` library
  - Installed into `jre/bin/server`

- Generates output to console and `hotspot_pid<pid>.log` file

Visualizing with JITWatch

- Open source JITWatch tool provides visualization of data:



- Also attempts to make optimization suggestions

Questions?

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