Applied Static Analysis
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Java Bytecode

A HARDWARE- AND OPERATING SYSTEM-INDEPENDENT BINARY FORMAT, KNOWN AS THE CLASS FILE FORMAT.

The Java® Virtual Machine Specification
Java SE 8 Edition
Specification: JSR-000337 Java® SE 8 Release Contents Specification ("Specification") Version: 8
Status: Proposed Final Draft
Release: January 2014

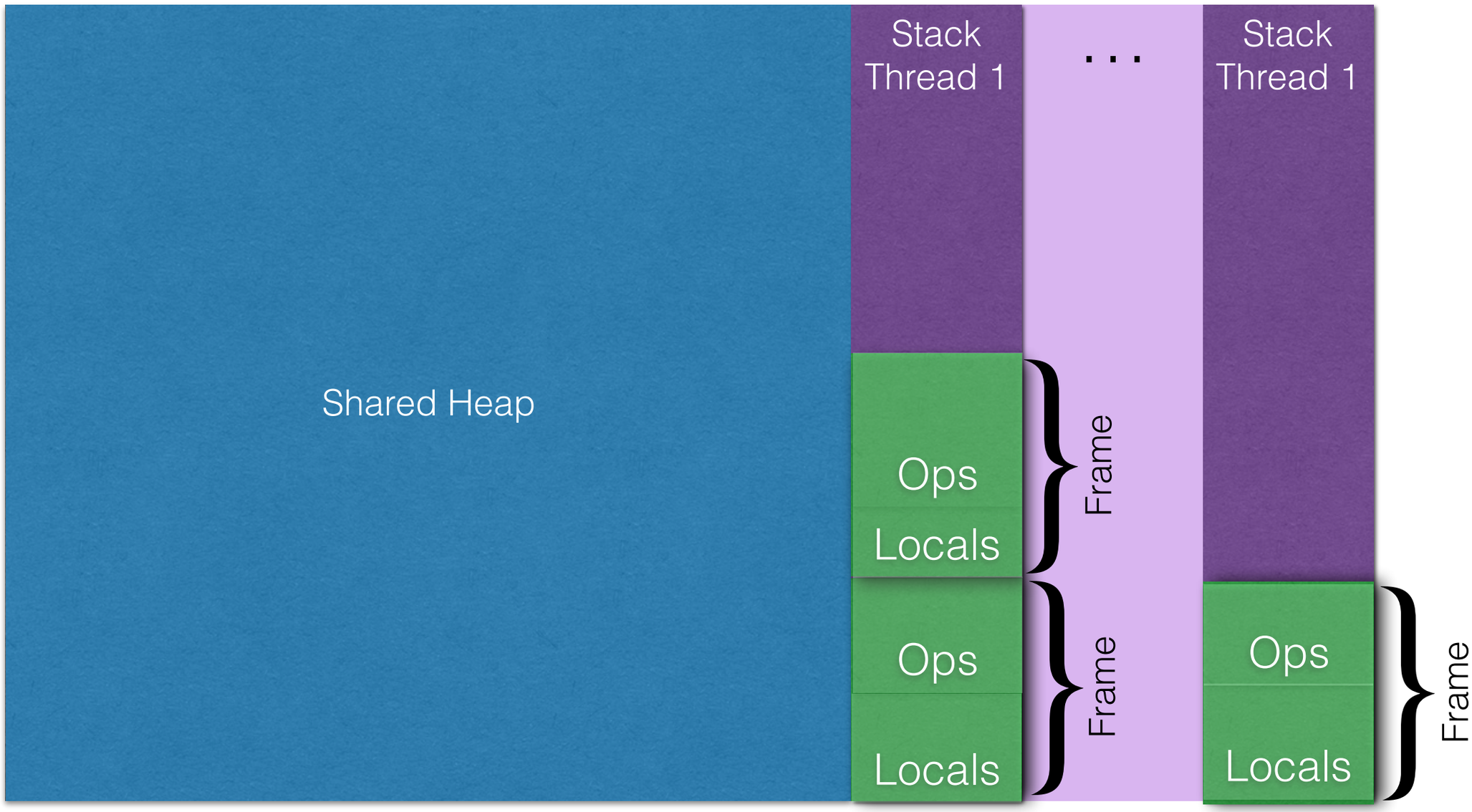
Structure of the Java Virtual Machine (JVM)

- Data types:
  - Primitive Types:
    `boolean`, `byte`, `short`, `int`, `char` *(computational type int; cat. **1**)*
    `long`, *(computational type long; cat. **2**)*
    `float`, *(computational type float; cat. **1**)*
    `double`, *(computational type long; cat. **2**)*
    `return address` *(computational type return address; cat. **1**)*
  - Reference Types: *(computational type reference value; cat. **1**)*
    `class`,
    `array`,
    `interface` `types`

Structure of the Java Virtual Machine (JVM)

- Run-time Data Areas
  - the `pc` (program counter) register contains the address of the instruction that is currently executed by a thread; each thread has its own pc
  - each JVM thread has a `private stack` which holds local variables and partial results
  - the `heap` which is shared among all threads
  - `frames` are allocated from a JVM thread's private stack when a method is invoked; each frame has its own array of `local variables` and `operand stack`
    - local variables are indexed
      - *a single local* variable can hold a value of type `boolean`, `byte`, `char`, `short`, `int`, `float`, `reference`, or `return address` (computational type category 1)
      - *a pair of local variables* can hold a value of type `long` or `double` (computational type category 2)
    - the `operand stack` is empty at creation time; an entry can hold any value
    - the `local variables` contains the parameters (including the implicit `this` parameter in local variable 0)

Structure of the Java Virtual Machine (JVM)



Structure of the Java Virtual Machine (JVM)

- Special Methods
  - the name of instance initialization methods (Java constructors) is "`<init>`"
  - the name of the class or interface initialization method (Java static initializer) is "`<clinit>`"

- Exceptions are instance of the class `Throwable` or one of its subclasses; exceptions are thrown if:
  - an `athrow` instruction was executed
  - an abnormal execution condition occurred (e.g., division by zero)

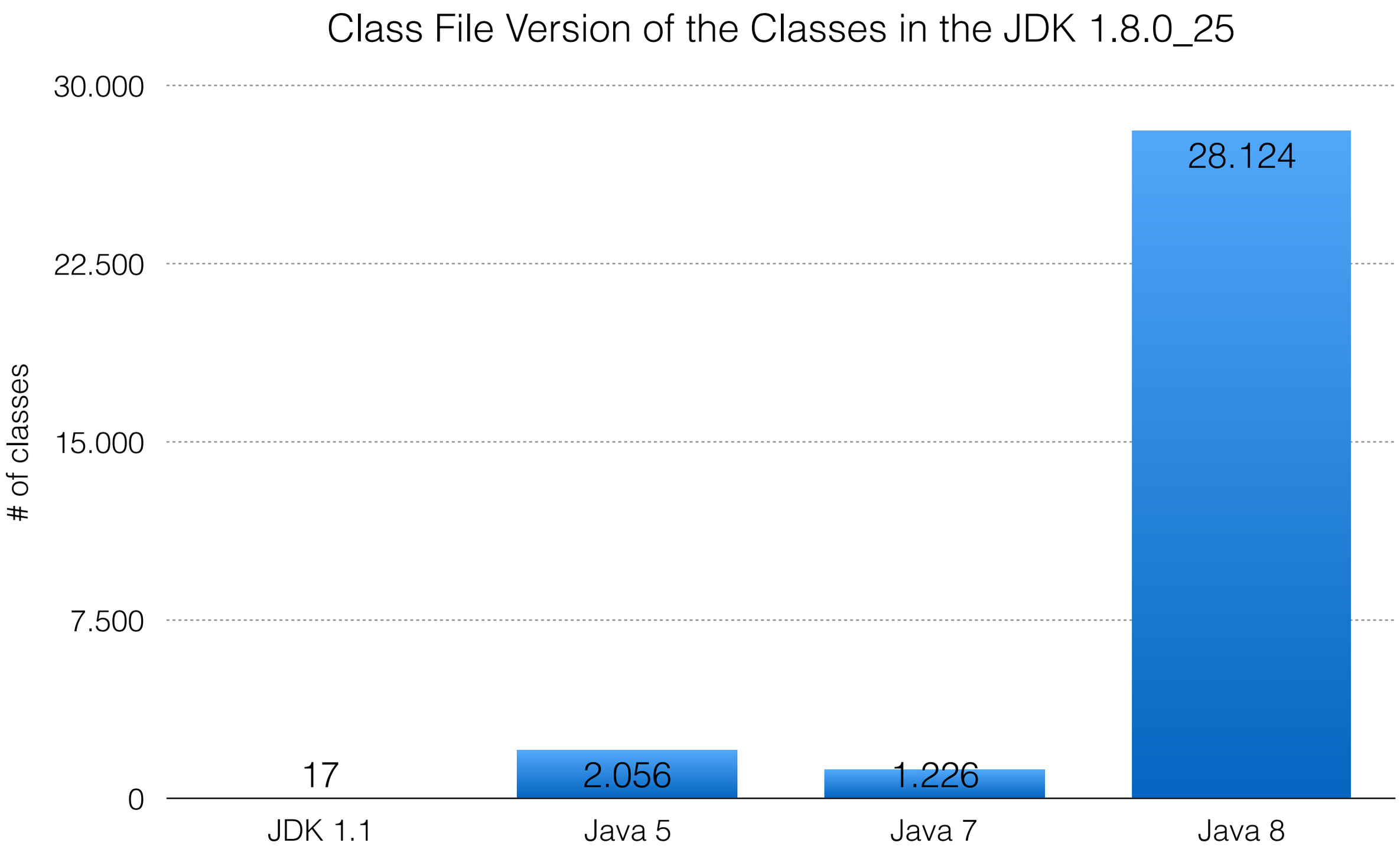
Structure of the Java Virtual Machine (JVM)

- Instruction Set Summary
  - an instruction consists of *a one-byte opcode* specifying the operation and zero or more operands (arguments to the operation)
  - most instructions *encode type information in their name*; in particular those operating on primitive types (e.g., `iadd`, `fadd`, `dadd`)
  - some are generic and are only restricted by the computational type category of the values (e.g. `swap`, `dup2`)

Structure of the Java Virtual Machine (JVM)

- Categories of Instructions
  - Load and store instructions (e.g., `aload_0`, `istore`(x))
    (Except of the load and store instructions, the only other instruction that manipulates a local variable is `iinc`.)
  - Arithmetic instructions (e.g., `iadd`, `iushr`)
  - (Primitive/Base) Type conversion instructions (e.g., `i2d,l2d,l2i`)
  - Object/Array creation and manipulation (e.g., `new`, `checkcast`)
  - (Generic) Operand Stack Management Instructions (e.g., `dup`)
  - Control Transfer Instructions (e.g., `itlt`, `if_icmplt, goto, jsr, ret`)'
    (Some are further modified using the `wide modifier`.)
    obsolete since Java 5
  - Method Invocation and Return instructions (e.g., `invokespecial`, `return`)
  - Throwing Exceptions (`athrow`)
  - Synchronization (`monitorenter`, `monitorexit`)

Obsolete Code in the JDK



Structure of the Java Virtual Machine (JVM)

- The maximum length of a method is 65536.
  (This is a frequent issue with generated code.)

- A method can have only 65536 local variables.
  (The maximum number of locals in the JDK is 142.)
  (The maximum number of locals in OPAL is/was 1136.)

- The maximum stack size of a single method is 65536.
  (The maximum stack size of any method in the JDK is 42.)

Java Bytecode

```
static int max(int i, int j) {
    if (i > j)
        return i;
    else
        return j;
}
```

PC	Instruction
0	iload_0
1	iload_1
2	if_icmple →7
5	iload_0
6	ireturn
7	iload_1
8	ireturn

Java Bytecode

```
static int max(int i, int j) {
    if (i > j)
        return i;
    else
        return j;
}
```

PC	Instruction	Operand Stack	Registers/Local Vars.
0	iload_0		0: an int 1: an int
1	iload_1	an int	0: an int 1: an int
2	if_icmple →7	an int an int	0: an int 1: an int
5	iload_0		0: int ∈ [-2147483647,*MAX*] 1: int ∈ [*MIN*,2147483646]
6	ireturn	int ∈ [-2147483647,*MAX*]	0: int ∈ [-2147483647,*MAX*] 1: int ∈ [*MIN*,2147483646]
7	iload_1		0: an int 1: an int
8	ireturn	an int	0: an int 1: an int

Java Bytecode - Loops

```
static int factorial(int n) {
    int r = 1;
    while (n > 0) {
        r *= n;
        n--;
    }
    return r;
}
```

PC	Instruction
0	iconst_1
1	istore_1
2	goto →12
5	iload_1
6	iload_0
7	imul
8	istore_1
9	iinc (lv=0,val=-1)
12	iload_0
13	ifgt →5
16	iload_1
17	ireturn

Java Bytecode - Object Creation

```
static int numberOfDigits(int i) {
     assert (i > 0);
     return ((int) Math.floor(Math.log10(i))) + 1;
 }
```

PC	Instruction	Code
0	getstatic TACDemo { boolean $assertionsDisabled }	assert(i > 0)
3	ifne →18	
6	iload_0	
7	ifgt →18	
10	new java.lang.AssertionError	
13	dup	
14	invokespecial java.lang.AssertionError { void <init> () }	
17	athrow	
18	iload_0	`Math.log10(i)`
19	i2d	
20	invokestatic java.lang.Math { double log10 (double) }	
23	invokestatic java.lang.Math { double floor (double) }	Math.floor(…)
26	d2i	(int) *“Typecast”*
27	iconst_1	1
28	iadd	+
29	ireturn	return

Java Bytecode - Basic Exception Handling

```
int tryCatch(Object o) {
    try {
        List<?> l = (List<?>) o;
        if (l.size() == 0)
            return -1 / l.size();
        else
            return 1;
    } catch (ClassCastException cce) {
        return 0;
    } catch (Error | RuntimeException e) {
        throw e;
    }
}
```

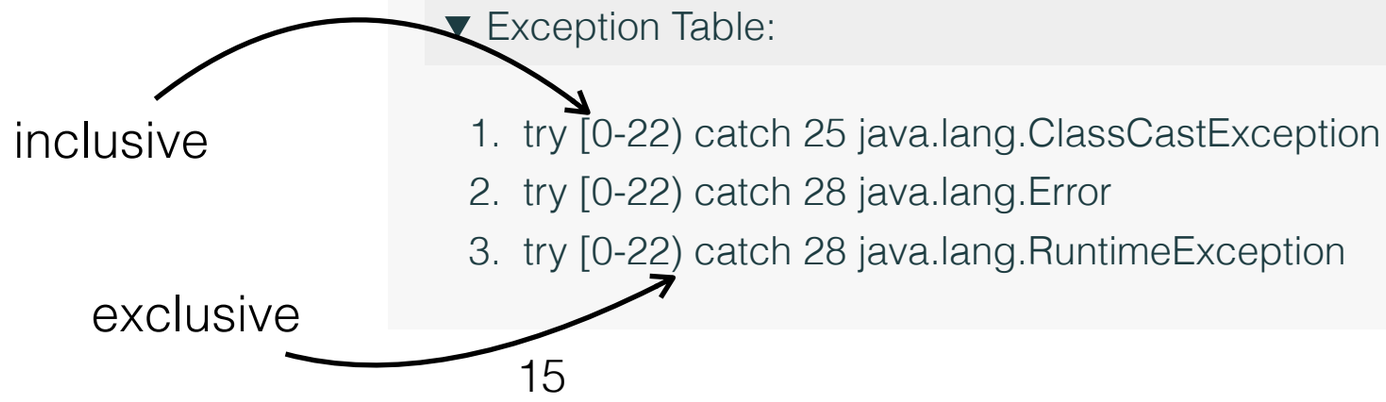
▼ Method Body (Size: 31 bytes, Max Stack: 2, Max Locals: 3)

PC	Line	Instruction		Exceptions
0	109	*aload_1*		
1	|	*checkcast*	java.util.List	
4	|	*astore_2*		
5	110	*aload_2*		
6	|	*invokeinterface*	java.util.List { int size () }	
11	|	*ifne*	23	
14	111	*iconst_m1*		
15	|	*aload_2*		
16	|	*invokeinterface*	java.util.List { int size () }	
21	|	*idiv*		
22	|	*ireturn*		
23	113	*iconst_1*		
24	|	*ireturn*		
25	114	*astore_2*		
26	115	*iconst_0*		
27	|	*ireturn*		
28	116	*astore_2*		
29	117	*aload_2*		
30	|	*athrow*		

Exceptions: 1: java.lang.ClassCastException; 2: java.lang.Error; 3: java.lang.RuntimeException

▼ Exception Table:

1. try [0-22) catch 25 java.lang.ClassCastException
2. try [0-22) catch 28 java.lang.Error
3. try [0-22) catch 28 java.lang.RuntimeException



Java Bytecode - Finally

```
int tryFinally(Object o) {
    int result = 0;
    try {
        if (o instanceof List<?>) {
            result = ((List<?>) o).size();
        } else {
            result = -1;
        }
        return result;
    } finally {
        result += 1;
    }
}
```

▼ Method Body (Size: 39 bytes, Max Stack: 1, Max Locals: 5)

PC	Line	Instruction			Exceptions
0	122	*iconst_0*			
1	|	*istore_2*			
2	124	*aload_1*			
3	|	*instanceof*	java.util.List		
6	|	*ifeq*	22		
9	125	*aload_1*			
10	|	*checkcast*	java.util.List		
13	|	*invokeinterface*	java.util.List { int size () }		
18	|	*istore_2*			
19	126	*goto*	24		
22	127	*iconst_m1*			
23	|	*istore_2*			
24	129	*iload_2*			
25	|	*istore*	4		
27	131	*iinc*	2	1	
30	129	*iload*	4		
32	|	*ireturn*			
33	130	*astore_3*			
34	131	*iinc*	2	1	
37	132	*aload_3*			
38	|	*athrow*			

Exceptions: 1: Any

▼ Exception Table:

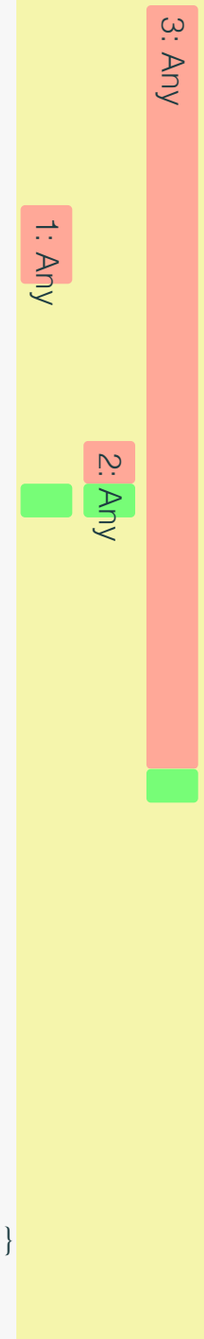
1. try [2-27) catch 33 Any

Java - Try With Resources

```
static int readFirstByte(String path) throws Exception {
    try (FileReader r = new FileReader(path)) {
        return r.read();
    }
}
```

▼ Method Body (Size: 59 bytes, Max Stack: 3, Max Locals: 4)

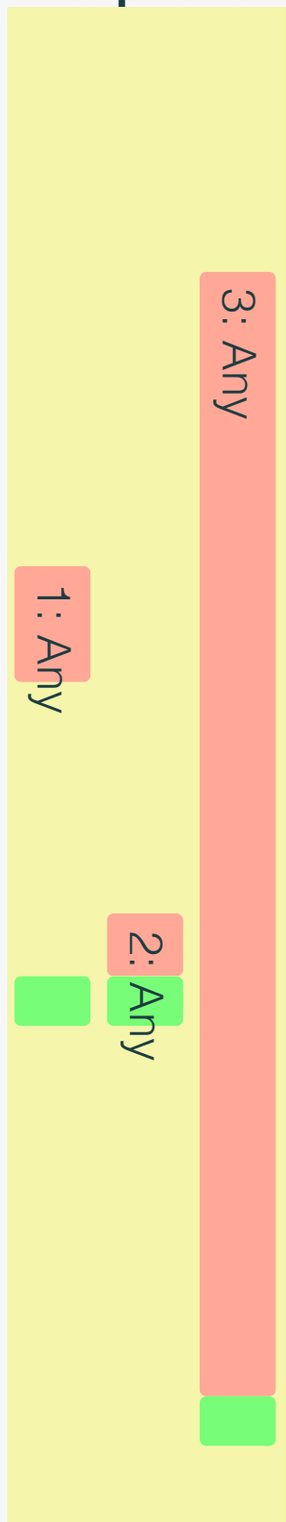
PC	Line	Instruction		Exceptions
0	138	*aconst_null*		
1	|	*astore_1*		
2	|	*aconst_null*		
3	|	*astore_2*		
4	|	*new*	java.io.FileReader	
7	|	*dup*		
8	|	*aload_0*		
9	|	*invokespecial*	java.io.FileReader { void <init> (java.lang.String) }	
12	|	*astore_3*		
13	139	*aload_3*		
14	|	*invokevirtual*	java.io.FileReader { int read () }	
17	140	*aload_3*		
18	|	*ifnull*	25	
21	|	*aload_3*		
22	|	*invokevirtual*	java.io.FileReader { void close () }	
25	139	*ireturn*		
26	|	*astore_1*		
27	140	*aload_3*		
28	|	*ifnull*	35	
31	|	*aload_3*		
32	|	*invokevirtual*	java.io.FileReader { void close () }	
35	|	*aload_1*		
36	|	*athrow*		
37	|	*astore_2*		
38	|	*aload_1*		
39	|	*ifnonnull*	47	
42	|	*aload_2*		
43	|	*astore_1*		
44	|	*goto*	57	
47	|	*aload_1*		
48	|	*aload_2*		
49	|	*if_acmpeq*	57	
52	|	*aload_1*		
53	|	*aload_2*		
54	|	*invokevirtual*	java.lang.Throwable { void addSuppressed (java.lang.Throwable) }	
57	|	*aload_1*		
58	|	*athrow*		



Java - Try With Resources

```
static int readFirstByte(String path) throws Exception {
    try (FileReader r = new FileReader(path)) {
        return r.read();
    }
}
```

PC	Line	Instruction		Exceptions
0	138	*aconst_null*		
1	|	*astore_1*		
2	|	*aconst_null*		
3	|	*astore_2*		
4	|	*new*	java.io.FileReader	
7	|	*dup*		
8	|	*aload_0*		
9	|	*invokespecial*	java.io.FileReader { void <init> (java.lang.String) }	
12	|	*astore_3*		
13	139	*aload_3*		
14	|	*invokevirtual*	java.io.FileReader { int read () }	
17	140	*aload_3*		
18	|	*ifnull*	25	
21	|	*aload_3*		
22	|	*invokevirtual*	java.io.FileReader { void close () }	
25	139	*ireturn*		
26	|	*astore_1*		
27	140	*aload_3*		
28	|	*ifnull*	35	
31	|	*aload_3*		
32	|	*invokevirtual*	java.io.FileReader { void close () }	
35	|	*aload_1*		
36	|	*athrow*		
37	|	*astore_2*		
38	|	*aload_1*		
39	|	*ifnonnull*	47	



Java Bytecode - Synchronization

```
public class TACDemo {

    private static volatile TACDemo instance;

    static TACDemo getInstance() {
        TACDemo instance = TACDemo.instance;
        // thread-safe double checked locking
        if (instance == null) {
            synchronized (TACDemo.class) {
                instance = TACDemo.instance;
                if (instance == null) {
                    instance = new TACDemo();
                    TACDemo.instance = instance;
                }
            }
        }
        return instance;
    }
}
```

PC	Instruction	Exception Handlers	
0	getstatic TACDemo { TACDemo instance }		
3	astore_0		
4	aload_0		
5	ifnonnull →41		
8	ldc TACDemo.class		
10	dup		
11	astore_1		
12	monitorenter		
13	getstatic TACDemo { TACDemo instance }	1: Any	
16	astore_0		
17	aload_0		
18	ifnonnull →33		
21	new TACDemo		
24	dup		
25	invokespecial TACDemo { void <init> () }		
28	astore_0		
29	aload_0		
30	putstatic TACDemo { TACDemo instance }		
33	aload_1		
34	monitorexit		
35	goto →41		
38	aload_1		2: Any
39	monitorexit		
40	athrow		
41	aload_0		
42	areturn		

```
static <T> List<T> sortIt(List<T> l) {
    l.sort(
      (T a, T b) -> { return a.hashCode() - b.hashCode(); }
    );
    return l;
}
```

```
static <T> List<T> sortIt(List<T> l) {
    l.sort((T a, T b) -> { return a.hashCode() - b.hashCode(); });
    return l;
}
```

static java.util.List sortIt(java.util.List)

Signature : <T:Ljava/lang/Object;>(Ljava/util/List<TT;>;)Ljava/util/List<TT;>;

▼ Method Body (Size: 13 bytes, Max Stack: 2, Max Locals: 1)

PC	Line	Instruction	
0	164	*aload_0*	
1	|	*invokedynamic*	(Bootstrap Method Attribute[0], java.util.Comparator compare ())
6	|	*invokeinterface*	java.util.List { void sort (java.util.Comparator) }
11	167	*aload_0*	
12	|	*areturn*	

▼ LineNumberTable

start_pc: 0, line_number: 164
start_pc: 11, line_number: 167

▼ LocalVariableTable

pc=[0 → 13) / lv=0 ⇒ java.util.List l

▼ LocalVariableTypeTable

pc=[0 → 13) / lv=0 ⇒ l : Ljava/util/List<TT;>;

```
static <T> List<T> sortIt(List<T> l) {
    l.sort((T a, T b) -> { return a.hashCode() - b.hashCode(); });
    return l;
}
```

static java.util.List sortIt(java.util.List)

Signature : <T:Ljava/lang/Object;>(Ljava/util/List<TT;>;)Ljava/util/List<TT;>;

▼ Method Body (Size: 13 bytes, Max Stack: 2, Max Locals: 1)

PC	Line	Instruction
0	164	*aload_0*
1	|	*invokedynamic* (Bootstrap Method Attribute[0], java.util.Comparator compare ())

MethodHandle(kind=REF_invokeStatic invokestatic C.m:(A*)T, java.lang.invoke.LambdaMetafactory { java.lang.invoke.CallSite metafactory (java.lang.invoke.MethodHandles$Lookup, java.lang.String, java.lang.invoke.MethodType, java.lang.invoke.MethodType, java.lang.invoke.MethodHandle, java.lang.invoke.MethodType) })

Parameters:

- MethodType(int (java.lang.Object, java.lang.Object))
- MethodHandle(
  kind=REF_invokeStatic invokestatic C.m:(A*)T,
  TACDemo { int lambda$0 (java.lang.Object, java.lang.Object) }
)
- MethodType(int (java.lang.Object, java.lang.Object))

```
static <T> List<T> sortIt(List<T> l) {
    l.sort((T a, T b) -> { return a.hashCode() - b.hashCode(); });
    return l;
}
```

static java.util.List sortIt(java.util.List)

Signature : <T:Ljava/lang/Object;>(Ljava/util/List<TT;>;)Ljava/util/List<TT;>;

▼ Method Body (Size: 13 bytes, Max Stack: 2, Max Locals: 1)

PC	Line	Instruction	
0	164	*aload_0*	
1	|	*invokedynamic*	(Bootstrap Method Attribute[0], java.util.Comparator compare ())
6	|	*invokeinterface*	java.util.List { void sort (java.util.Comparator) }
11	167		
12	|		

▼ LineNumb

start_pc: 0, lin
start_pc: 11, li

▼ LocalVaria

pc=[0 → 13) /

▼ LocalVaria

pc=[0 → 13) /

private static [SYNTHETIC] int lambda$0(java.lang.Object, java.lang.Object)

▼ Method Body (Size: 10 bytes, Max Stack: 2, Max Locals: 2)

PC	Line	Instruction	
0	165	*aload_0*	
1	|	*invokevirtual*	java.lang.Object { int hashCode () }
4	|	*aload_1*	
5	|	*invokevirtual*	java.lang.Object { int hashCode () }
8	|	*isub*	
9	|	*ireturn*	

▼ LineNumberTable

start_pc: 0, line_number: 165

▼ LocalVariableTable

pc=[0 → 10) / lv=0 ⇒ java.lang.Object a
pc=[0 → 10) / lv=1 ⇒ java.lang.Object b

▼ LocalVariableTypeTable

pc=[0 → 10) / lv=0 ⇒ a : TT;
pc=[0 → 10) / lv=1 ⇒ b : TT;

Analyzing Java Bytecode works (very) well, because **Java compilers deliberately don't optimize.**

```
static long optimizableExpression(double d, int i, long l) {
    return (long)((d * d) + i) * 0l;
}
```

PC	Instruction
0	dload_0
1	dload_0
2	dmul
3	iload_2
4	i2d
5	dadd
6	d2l
7	lconst_0
8	lmul
9	lreturn

Example

Analyzing Java Bytecode works (very) well, because **Java compilers deliberately don’t optimize.**

```
static void optimizableIndexInc(int[] is, int i) {
    is[i++] = 0;
    is[i++] = 1;
}
```

PC	Instruction
0	aload_0
1	iload_1
2	iinc (lv=1,val=1)
5	iconst_0
6	iastore
7	aload_0
8	iload_1
9	iinc (lv=1,val=1)
12	iconst_1
13	iastore
14	return

Example

Analyzing Java Bytecode works (very) well, because **Java compilers deliberately don't optimize.**

```
int always9() {
      int i = 3;
      int j = 3;
      return i * j;
}
```

PC	Instruction
0	iconst_3
1	istore_1
2	iconst_3
3	istore_2
4	iload_1
5	iload_2
6	imul
7	ireturn

Example

~~Analyzing Java Bytecode works (very) well, because Java compilers deliberately don't optimize.~~

Java compilers perform constant propagation for final local variables and final fields (primitive values and Strings). Expressions are evaluated if all parameters are primitive constants.

```
int always6() {
    final int i = 3;
    final int j = 2;
    return i * j;
}
```

PC	Instruction
0	iconst_3
1	istore_1
2	iconst_2
3	istore_2
4	bipush 6
6	ireturn

```
int always8() {
    return 4 * 2;
}
```

PC	Instruction
0	bipush 8
2	ireturn

```
double eXpi() { return Math.E * Math.PI; }
```

PC	Instruction
0	ldc2_w 8.539734222673566d
3	dreturn

Example

Summary

Sources of Potentially Dead Code Created by Java Compilers

- Finally blocks are generally included twice.
- Switches always have default branches.
- Constant expressions are evaluated.
- Constant propagation for final (local) variables/final fields is performed. (This includes primitive types and “Strings”).

Other Peculiarities

- Types are represented using binary notation. In binary notation packages are separated using “/“: e.g., java/lang/Object.
- The JVM has no “negate” instruction. A negation in Java (`!b`) is compiled to an `if` instruction followed by a push of the corresponding value.
- The JVM has no direct support for shortcut-evaluation (&&, ||).
- (Reliably) identifying anonymous inner classes is broken for older class files.
- The switch instructions are four byte aligned.
- The instruction set is not orthogonal; i.e., to achieve a certain effect many instructions exit.
- The catch block is not immediately available.

Three-Address Code

Three-Address Code (TAC)

- Three-address code is a sequence of statements with the general form:
  `x = y op z`

- where **x**,**y** and **z** are (local variable) names, constants (in case of **y** and **z**) or compiler-generated temporaries

- The name was chosen, because “most” statements use three addresses: two for the *operators* and *one to store the result*

General Types of Three-Address Statements

- **Assignment** statements `x = y bin_op z` or `x = unary_op z`
- **Copy** statements `x = y`
- **Unconditional jumps**: `goto l` (and `jsr l`, `ret` in case of Java bytecode)
- **Conditional jumps**: `if (x rel_op y) goto l` (else fall through), `switch`
- **Method call and return**: `invoke(m, params)`, `return x`
- **Array access**: `a[i]` or `a[i] = x`
- *More IR specific types.*

Converting Java Bytecode to Three-Address Code

- Core Idea:

  - Compute for each instruction the current stack layout by following the control flow; i.e., compute the types of values found on the stack before the instruction is evaluated.
    (The JVM specification guarantees that the operand stack always has the same layout independent of the taken path.)

  - Assign each local variable to a variable where the name is based on the local variable index.
    E.g., an `iinc(lv=1,val=1)` instruction is transformed into the three address code: `r_1 = r_1 + 1`

  - Assign each variable on the operand stack to a corresponding local variable with an index based on the position on the stack.
    E.g., if the operand stack is empty and we push the constant `1`, then the three address code would be: `op_0 = 1;` if we would then push another value `2` then the code would be: `op_1 = 2` and an addition of the two values would be: `op_0 = op_0 + op_1`

Converting Java Bytecode to Three-Address Code

```
static int numberOfDigits(int i) {
     return ((int) Math.floor(Math.log10(i))) + 1;
 }
```

PC	Instruction	Stack Layout (before execution)	Three-Address Code
	initialization		`r_0 = i; // parameter`
0	iload_0		`op_0 = r_0;`
1	i2d	0: Integer Value	`op_0 = (double) op_0;`
2	invokestatic java.lang.Math.log10 (double):double	0: Double Value	`op_0 = Math.log10(op_0);`
5	invokestatic java.lang.Math.floor(double):double	0: Double Value	`op_0 = Math.floor(op_0);`
8	d2i	0: Double Value	`op_0 = (int) op_0;`
9	iconst_1	0: Integer Value	`op_1 = 1;`
10	iadd	1: Integer Value 0: Integer Value	`op_0 = op_0 + op_1;`
11	ireturn	0: Integer Value	`return op_0;`

Java Bytecode vs. Three-Address Code

Java

```
static int max(int i, int j) {
    if (i > j)
        return i;
    else
        return j;
}
```

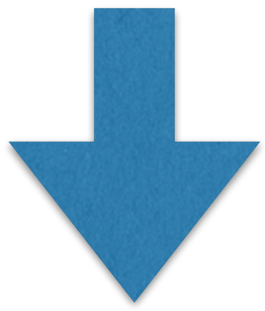
Bytecode

PC	Instruction
0	iload_0
1	iload_1
2	if_icmple →7
5	iload_0
6	ireturn
7	iload_1
8	ireturn

Three Address Code

```
0: r_0 = i;
1: r_1 = j;
2: op_0 = r_0;
3: op_1 = r_1;
4: if(op_0 <= op_1) goto 7;
5: op_0 = r_0;
6: return op_0;
7: op_0 = r_1;
8: return op_0;
```

After (Peephole) Optimizations



```
0: if(i <= j) goto 2;
1: return i;
2: return j;
```

Java Bytecode vs. Three-Address Code

Java

```
static int factorial(int n) {
    int r = 1;
    while (n > 0) {
        r *= n;
        n--;
    }
    return r;
}
```

Bytecode

PC	Instruction
0	iconst_1
1	istore_1
2	goto →12
5	iload_1
6	iload_0
7	imul
8	istore_1
9	iinc 0, -1
12	iload_0
13	ifgt →5
16	iload_1
17	ireturn

Three Address Code

```
0: r_0 = n;
1: op_0 = 1;
2: r_1 = op_0;
3: goto 9;
4: op_0 = r_1;
5: op_1 = r_0;
6: op_0 = op_0 * op_1;
7: r_1 = op_0;
8: r_0 = r_0 + -1;
9: op_0 = r_0;
10: if(op_0 > 0) goto 4;
11: op_0 = r_1;
12: return op_0;
```

After (Peephole) Optimizations

```
0: r_0 = n;
1: r_1 = 1;
2: goto 5;
3: r_1 = r_1 * r_0;
4: r_0 = r_0 + -1;
5: if(r_0 > 0) goto 3;
6: return r_1;
```

A Three-Address Code for Java Bytecode

Basic Statements

```
Assignment(
        pc:             PC,
        targetVar:      Var,
        expr:           Expr
)

Goto(pc: PC, target: Int)

JumpToSubroutine(pc: PC, target: Int)
Ret(pc: PC, returnAddressVar: Var)

Nop(pc: PC)

If(
        pc:             PC,
        left:           ValExpr,
        condition:      RelationalOperator,
        right:          ValExpr,
        target:         Int
)
Switch(
        pc:             PC,
        defaultTarget:  PC,
        index:          ValExpr,
        npairs:         IndexedSeq[(Int, PC)]
)
```

```
ReturnValue(pc: PC, expr: ValExpr)
Return(pc: PC)

ArrayStore(
    pc:         PC,
    arrayRef:   Var,
    index:      ValExpr,
    value:      ValExpr
)

Throw(pc: PC, exception: Var)

MonitorEnter(pc: PC, objRef: Var)
MonitorExit(pc: PC, objRef: Var)
```

A Three-Address Code for Java Bytecode

Field Access and Method Call Statements

```
PutStatic(
    pc:             PC,
    declaringClass: ObjectType,
    name:           String,
    value:          ValExpr
)
PutField(
    pc:             PC,
    declaringClass: ObjectType,
    name:           String,
    objRef:         Var,
    value:          ValExpr
)
```

```
NonVirtualMethodCall(
    pc:             PC,
    declaringClass: ReferenceType,
    name:           String,
    descriptor:     MethodDescriptor,
    receiver:       Var,
    params:         List[ValExpr]
)
VirtualMethodCall(
    pc:             PC,
    declaringClass: ReferenceType,
    name:           String,
    descriptor:     MethodDescriptor,
    receiver:       Var,
    params:         List[ValExpr]
)
StaticMethodCall(
    pc:             PC,
    declaringClass: ReferenceType,
    name:           String,
    descriptor:     MethodDescriptor,
    params:         List[ValExpr]
)
```

A Three-Address Code for Java Bytecode

Expressions

```
InstanceOf(pc: PC, value: Var, t: ReferenceType)
Checkcast(pc: PC, value: Var, t: ReferenceType)

Compare(
        pc:         PC,
        left:       ValExpr,
        condition:  RelationalOperator,
        right:      ValExpr
)

BinaryExpr(
        pc:   PC,
        cTpe: ComputationalType,
        op:   BinaryArithmeticOperator,
        left: ValExpr, right: ValExpr
)

PrefixExpr(
        pc:       PC,
        cTpe:     ComputationalType,
        op:       UnaryArithmeticOperator,
        operand:  ValExpr
)

PrimitiveTypecastExpr(
        pc:         PC,
        targetTpe:  BaseType,
        operand:    ValExpr
)

New(pc: PC, tpe: ObjectType)

NewArray(
        pc:     PC,
        counts: List[ValExpr],
        tpe:    ArrayType
)
ArrayLoad(pc: PC, index: Var, arrayRef: Var)
ArrayLength(pc: PC, arrayRef: Var)
```

ValExpr

```
Param(cTpe: ComputationalType, name: String)
SimpleVar(id: Int, cTpe: ComputationalType)

IntConst(pc: PC, value: Int)
LongConst(pc: PC, value: Long)
FloatConst(pc: PC, value: Float)
DoubleConst(pc: PC, value: Double)
StringConst(pc: PC, value: String)
ClassConst(pc: PC, value: ReferenceType)

NullExpr(pc: PC)
```

A Three-Address Code for Java Bytecode

Expressions

```
GetField(
        pc:                 PC,
        declaringClass:     ObjectType,
        name:               String,
        objRef:             ValExpr
)
GetStatic(
        pc:                 PC,
        declaringClass:     ObjectType,
        name:               String
)

InvokeDynamic(
        pc:                 PC,
        bootstrapMethod:    BootstrapMethod,
        name:               String,
        descriptor:         MethodDescriptor,
        params:             List[Expr]
)
MethodTypeConst(pc: PC, desc: MethodDescriptor)
MethodHandleConst(pc: PC, desc: MethodHandle)
```

```
NonVirtualFunctionCall(
    pc:                 PC,
    declaringClass:     ReferenceType,
    name:               String,
    descriptor:         MethodDescriptor,
    receiver:           Expr,
    params:             List[Expr]
)

VirtualFunctionCall(
    pc:                 PC,
    declaringClass:     ReferenceType,
    name:               String,
    descriptor:         MethodDescriptor,
    receiver:           Expr,
    params:             List[Expr]
)

StaticFunctionCall(
    pc:                 PC,
    declaringClass:     ReferenceType,
    name:               String,
    descriptor:         MethodDescriptor,
    params:             List[Expr]
)
```

Control-Flow Graph

- The control-flow graph (CFG) represents the control flow of a single method.

- Each node represents a **basic block**. A basic block is a maximal-length sequence of statements without jumps in and out (and no exceptions are thrown by intermediate instructions).

- The arcs represent the inter-node control flow.

Control-Flow Graph

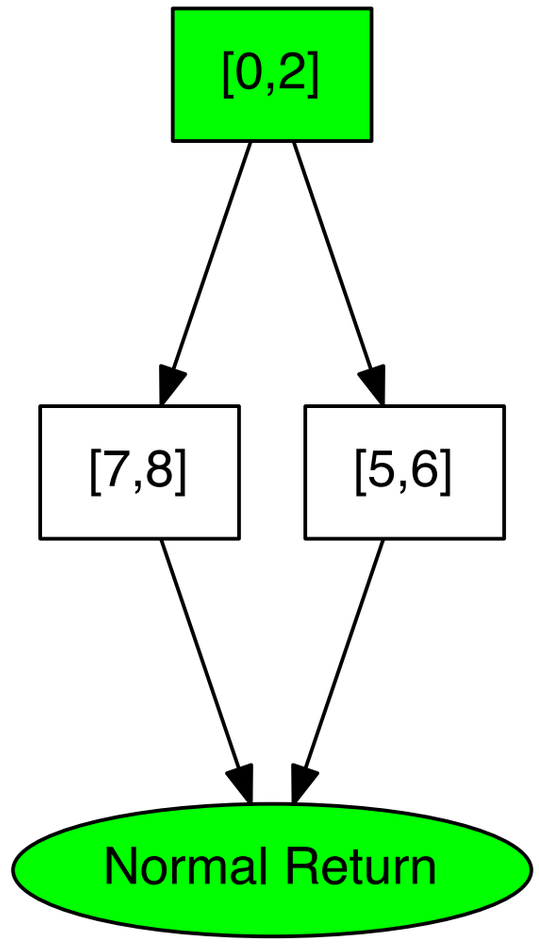
Java

```
static int max(int i, int j) {
    if (i > j)
        return i;
    else
        return j;
}
```

Bytecode

PC	Instruction
0	iload_0
1	iload_1
2	if_icmple →7
5	iload_0
6	ireturn
7	iload_1
8	ireturn

CFG



Loops - Control-Flow Graph

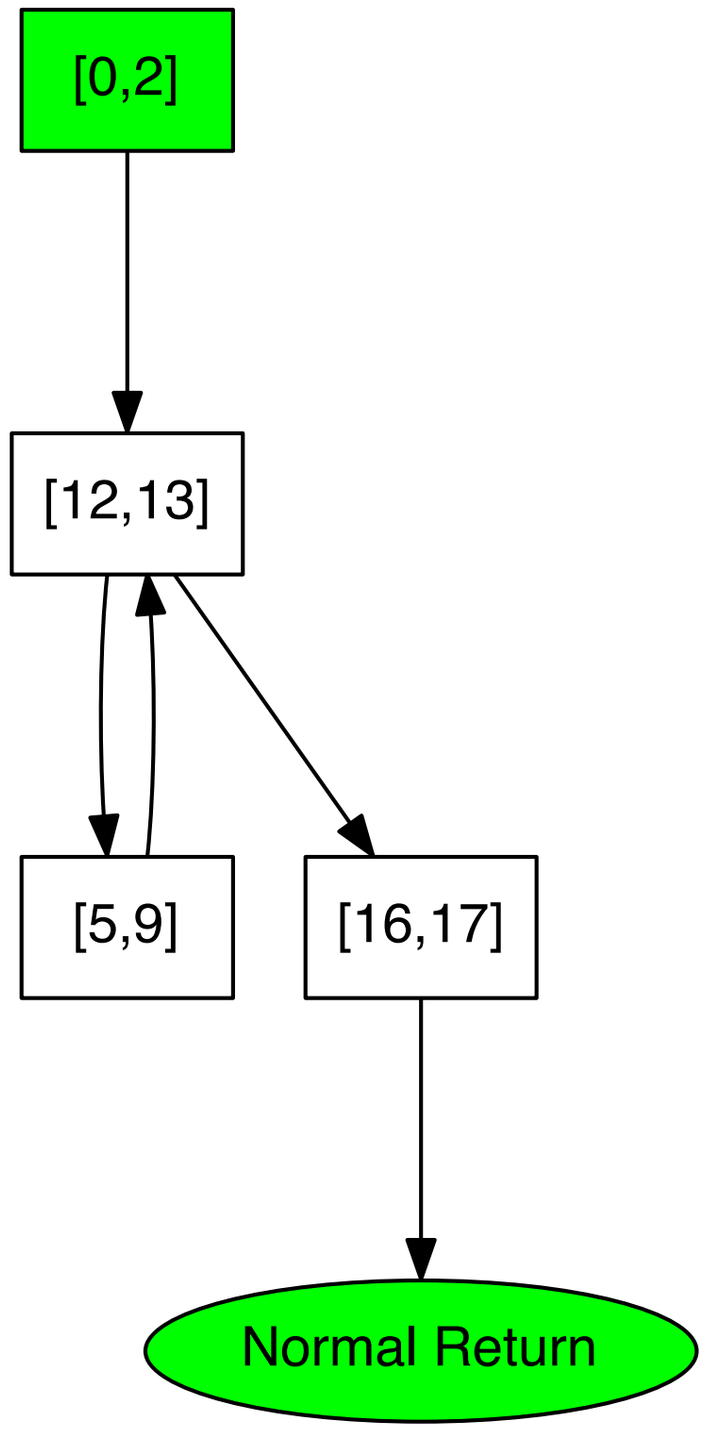
Java

```
static int factorial(int n) {
    int r = 1;
    while (n > 0) {
        r *= n;
        n--;
    }
    return r;
}
```

Bytecode

PC	Instruction
0	iconst_1
1	istore_1
2	goto →12
5	iload_1
6	iload_0
7	imul
8	istore_1
9	iinc (lv=0,val=-1)
12	iload_0
13	ifgt →5
16	iload_1
17	ireturn

CFG

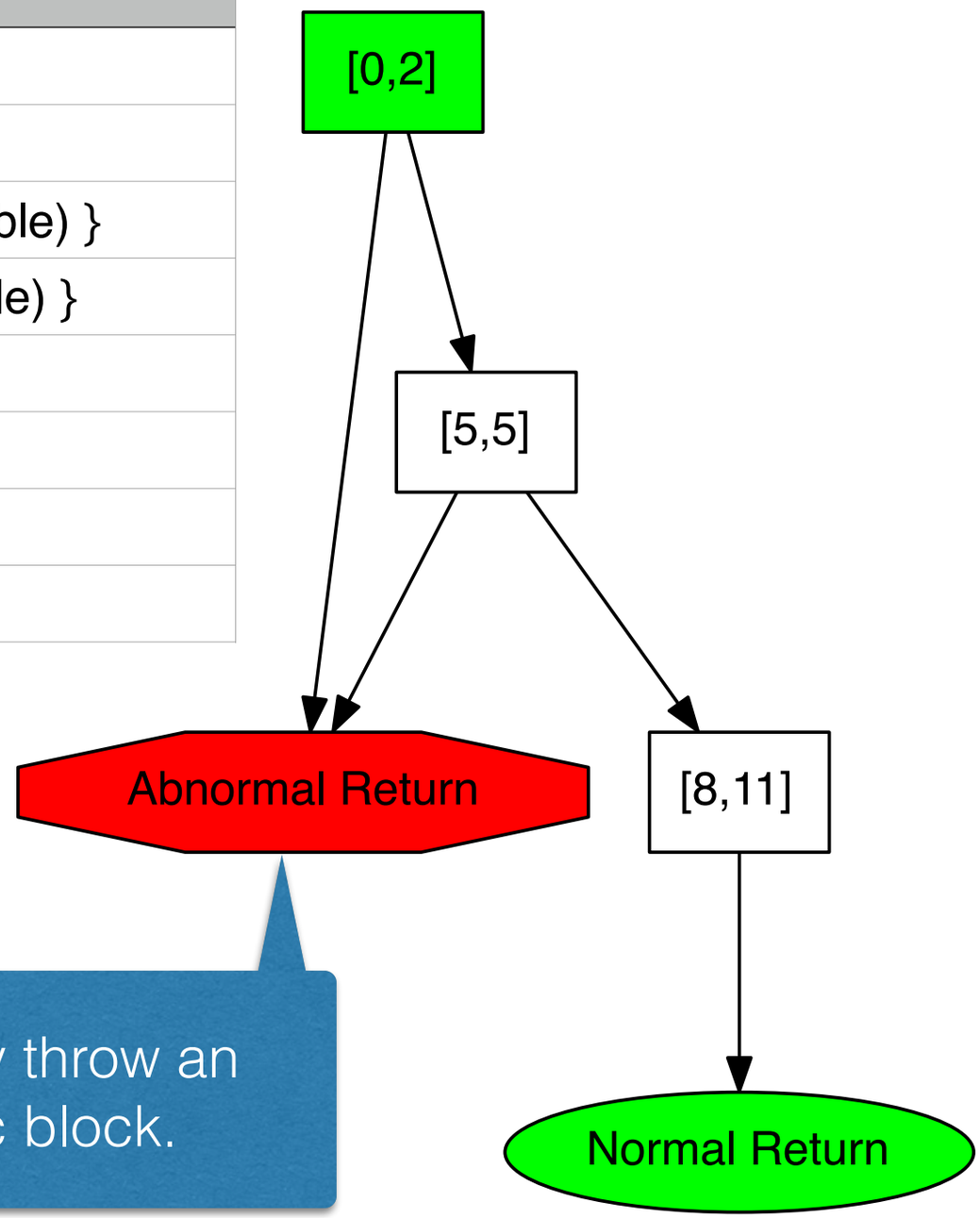


Java Bytecode

```
static int baseNumberOfDigits(int i) {
     return ((int) Math.floor(Math.log10(i))) + 1;
 }
```

PC	Instruction
0	iload_0
1	i2d
2	invokestatic java.lang.Math { double log10 (double) }
5	invokestatic java.lang.Math { double floor (double) }
8	d2i
9	iconst_1
10	iadd
11	ireturn

CFG



Every instruction that may throw an exception ends a basic block.

Java Bytecode - Finally

```
int tryFinally(Object o) {
    int result = 0;
    try {
        if (o instanceof List<?>) {
            result = ((List<?>) o).size();
        } else {
            result = -1;
        }
        return result;
    } finally {
        result += 1;
    }
}
```

▼ Method Body (Size: 39 bytes, Max Stack: 1, Max Locals: 5)

PC	Line	Instruction			Exceptions
0	122	*iconst_0*			
1	|	*istore_2*			
2	124	*aload_1*			
3	|	*instanceof*	java.util.List		
6	|	*ifeq*	22		
9	125	*aload_1*			
10	|	*checkcast*	java.util.List		
13	|	*invokeinterface*	java.util.List { int size () }		
18	|	*istore_2*			
19	126	*goto*	24		
22	127	*iconst_m1*			
23	|	*istore_2*			
24	129	*iload_2*			
25	|	*istore*	4		
27	131	*iinc*	2	1	
30	129	*iload*	4		
32	|	*ireturn*			
33	130	*astore_3*			
34	131	*iinc*	2	1	
37	132	*aload_3*			
38	|	*athrow*			

Exceptions: 1: Any

▼ Exception Table:

1. try [2-27) catch 33 Any

Java Bytecode - Finally

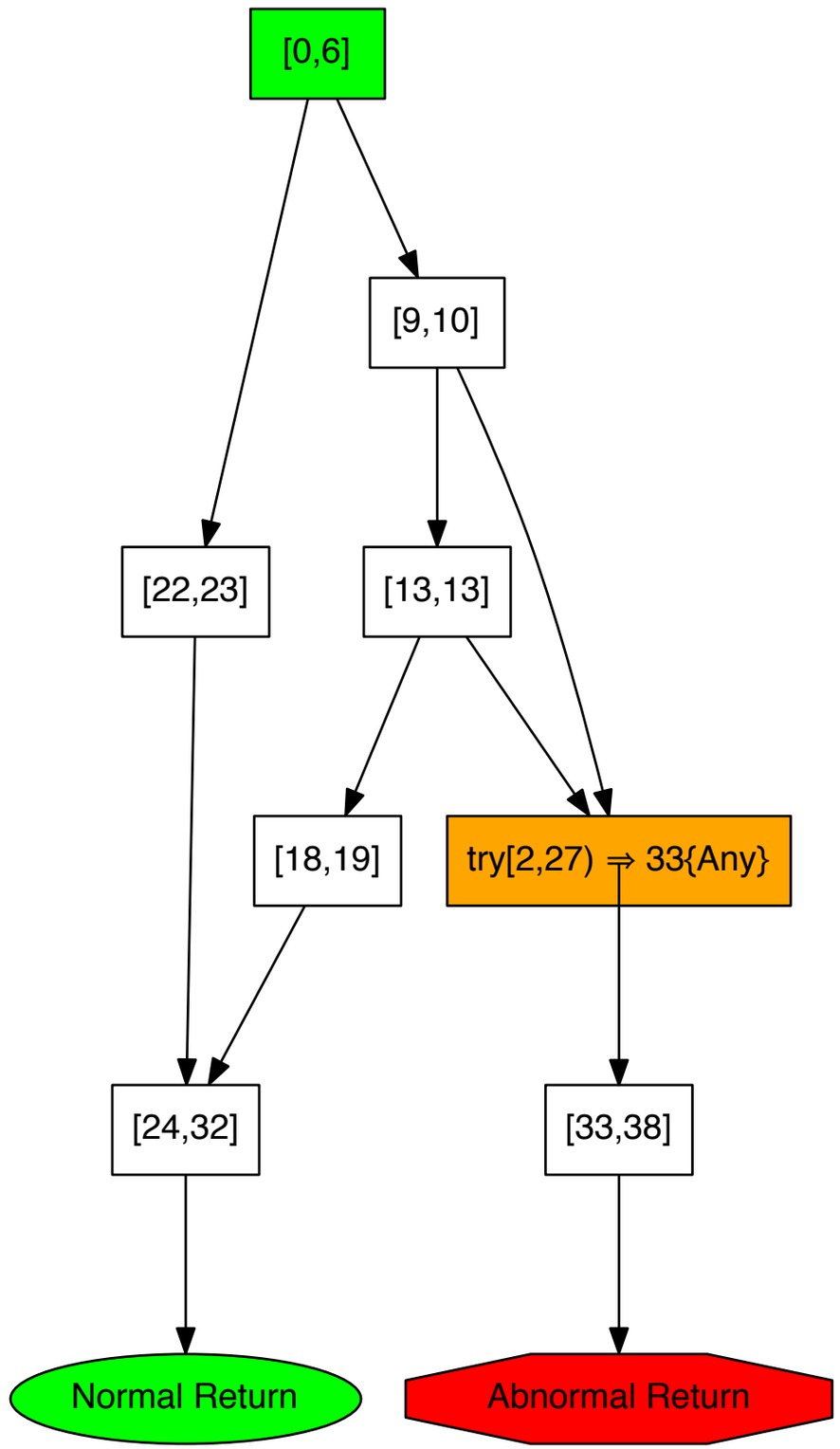
▼ Method Body (Size: 39 bytes, Max Stack: 1, Max Locals: 5)

PC	Line	Instruction			Exceptions
0	122	*iconst_0*			
1	|	*istore_2*			
2	124	*aload_1*			
3	|	*instanceof*	java.util.List		
6	|	*ifeq*	22		
9	125	*aload_1*			
10	|	*checkcast*	java.util.List		
13	|	*invokeinterface*	java.util.List { int size () }		
18	|	*istore_2*			
19	126	*goto*	24		
22	127	*iconst_m1*			
23	|	*istore_2*			
24	129	*iload_2*			
25	|	*istore*	4		
27	131	*iinc*	2	1	
30	129	*iload*	4		
32	|	*ireturn*			
33	130	*astore_3*			
34	131	*iinc*	2	1	
37	132	*aload_3*			
38	|	*athrow*			

1: Any

▼ Exception Table:

1. try [2-27) catch 33 Any



The CFG is an over approximation; it represents all paths.

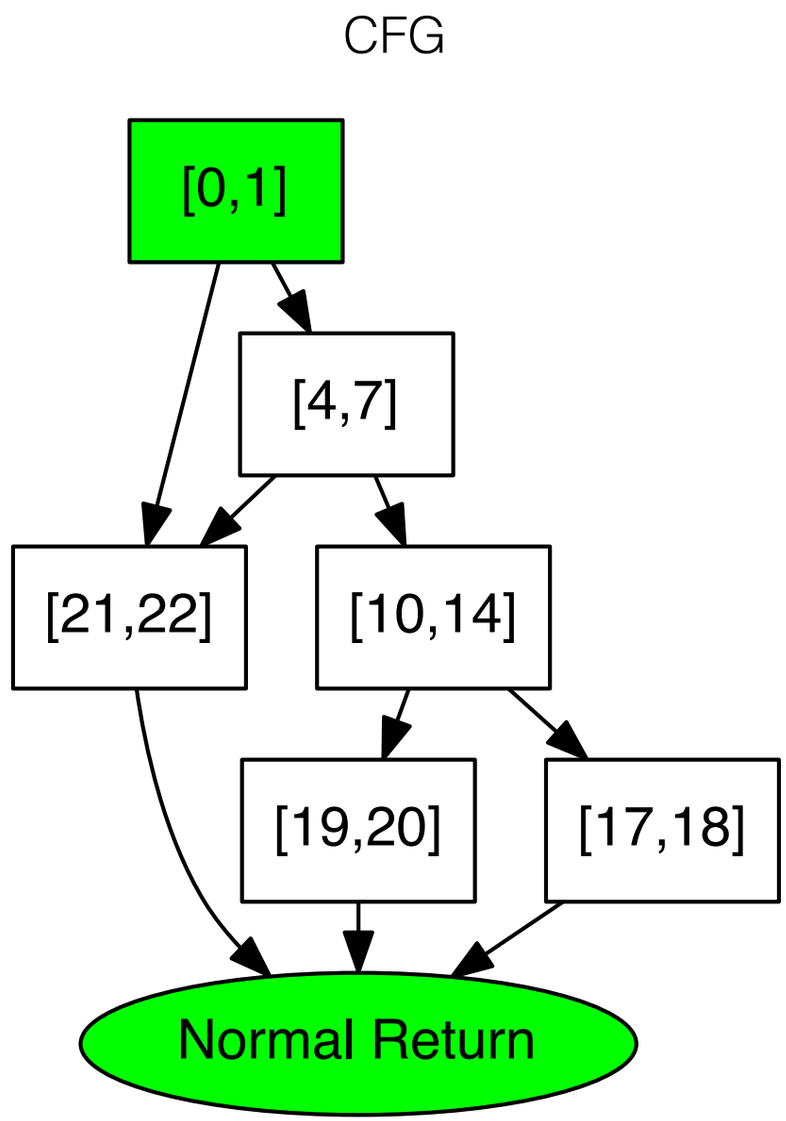
```
static boolean checkIt(int a, int b) {
    if (b < 0) {
        if (a < 100) {
            if( b > 1000)
                return true;
            else
                return false;
        }
    }
    return true;
}
```

Java

Bytecode

PC	Instruction
0	iload_1
1	ifge21
4	iload_0
5	bipush 100
7	if_icmpge →21
10	iload_1
11	sipush 1000
14	if_icmple →19
17	iconst_1
18	ireturn
19	iconst_0
20	ireturn
21	iconst_1
22	ireturn

CFG

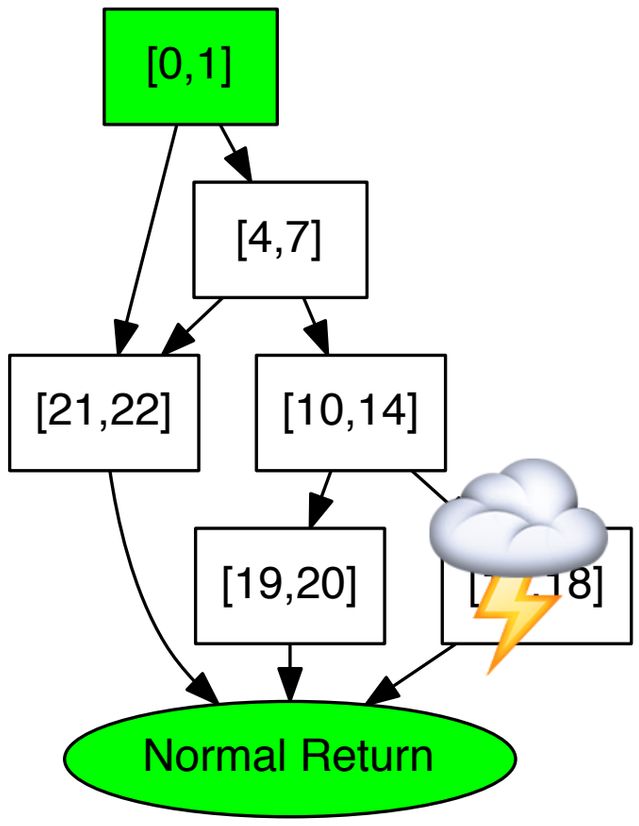


The CFG is an over approximation.

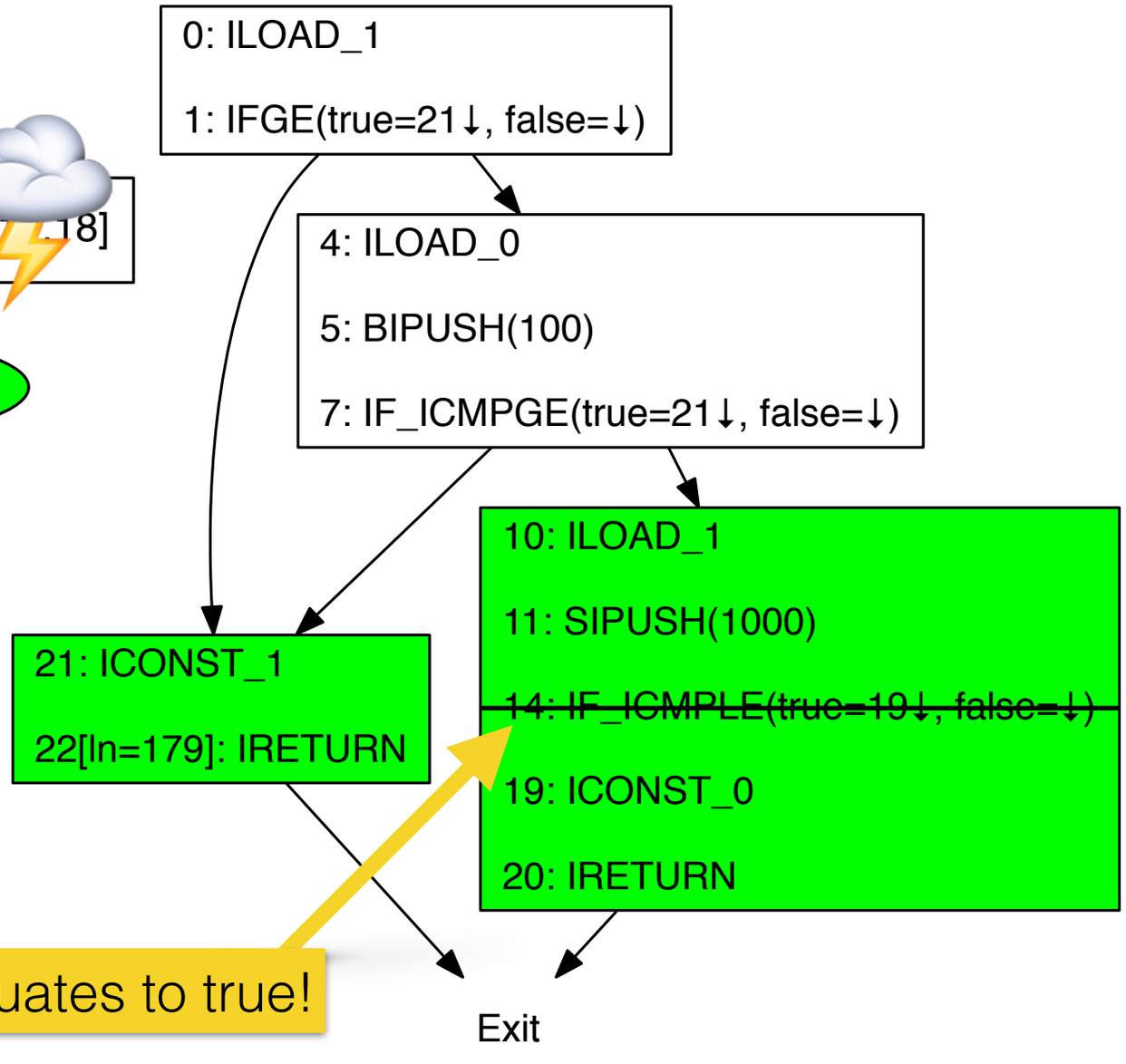
Bytecode

PC	Instruction
0	iload_1
1	ifge21
4	iload_0
5	bipush 100
7	if_icmpge →21
10	iload_1
11	sipush 1000
14	if_icmple →19
17	iconst_1
18	ireturn
19	iconst_0
20	ireturn
21	iconst_1
22	ireturn

Conservative CFG



CFG computed based on the result of an abstract interpretation



The “if” always evaluates to true!

Dominator Tree

- A node **d** of a (control-) flow graph *dominates* node **n**, if every path from the *initial node* of the flow graph to **n** goes through **d**.
  (Every node dominates itself.)

- In a dominator tree the initial node is the *unique* root node and each node **d** only dominates its descendants.

- Dominator information is useful in identifying loops; by identifying the header and the back edge.

Loops - CFG and Dominator Tree

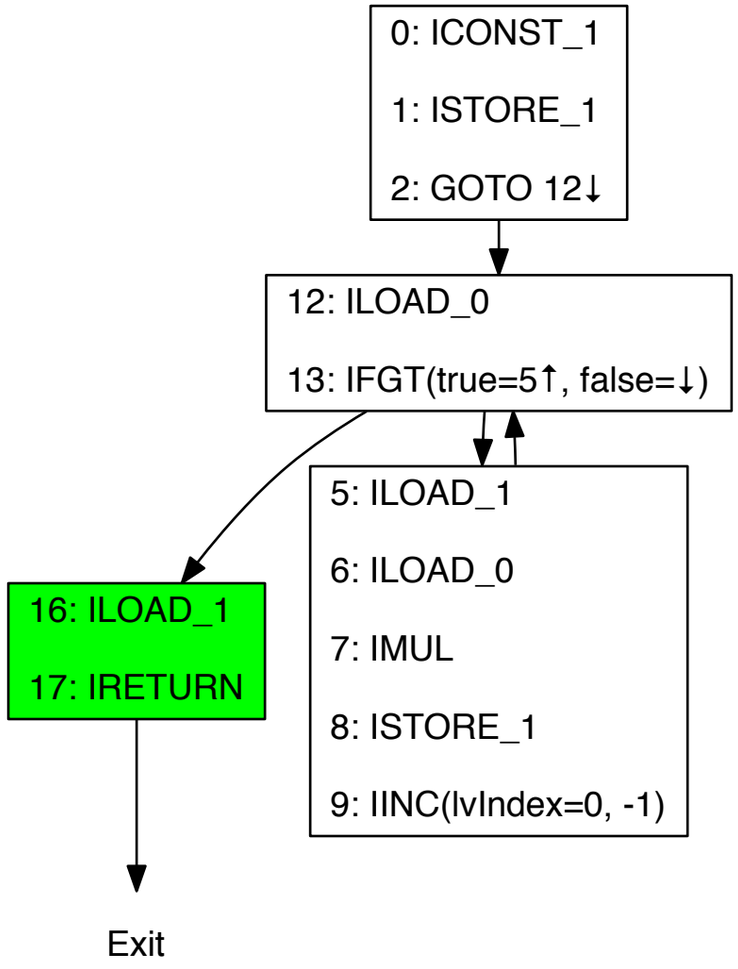
Java

```
static int factorial(int n) {
    int r = 1;
    while (n > 0) {
        r *= n;
        n--;
    }
    return r;
}
```

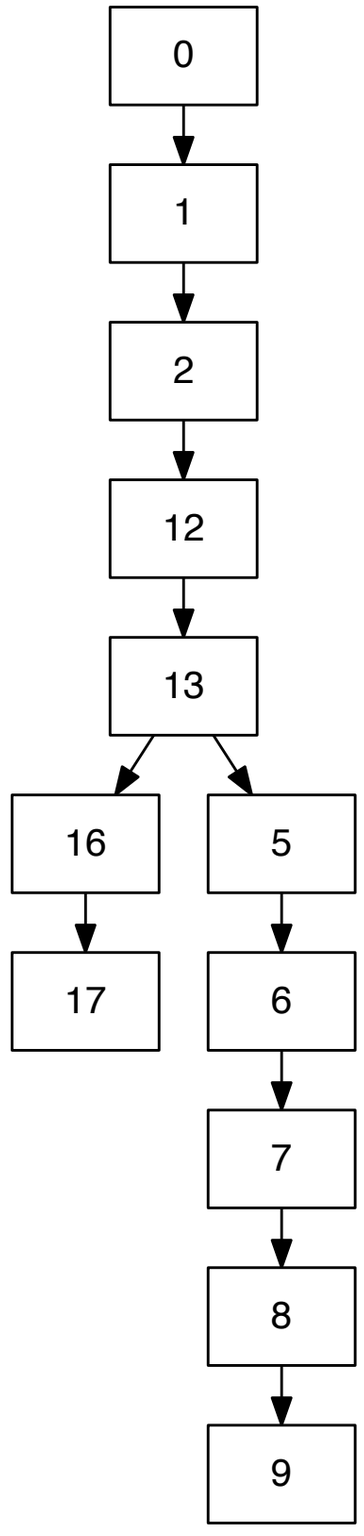
Bytecode

PC	Instruction
0	iconst_1
1	istore_1
2	goto →12
5	iload_1
6	iload_0
7	imul
8	istore_1
9	iinc (lv=0,val=-1)
12	iload_0
13	ifgt →5
16	iload_1
17	ireturn

CFG



Dominator Tree
(Instruction Level)



Post-Dominator Tree

- The post-dominator tree is the dominator tree computed using the *reverse* control flow graph.

- The reverse control flow graph is the control flow graph where all edges are reversed and — *if necessary* — a new artificial unique root node is added.

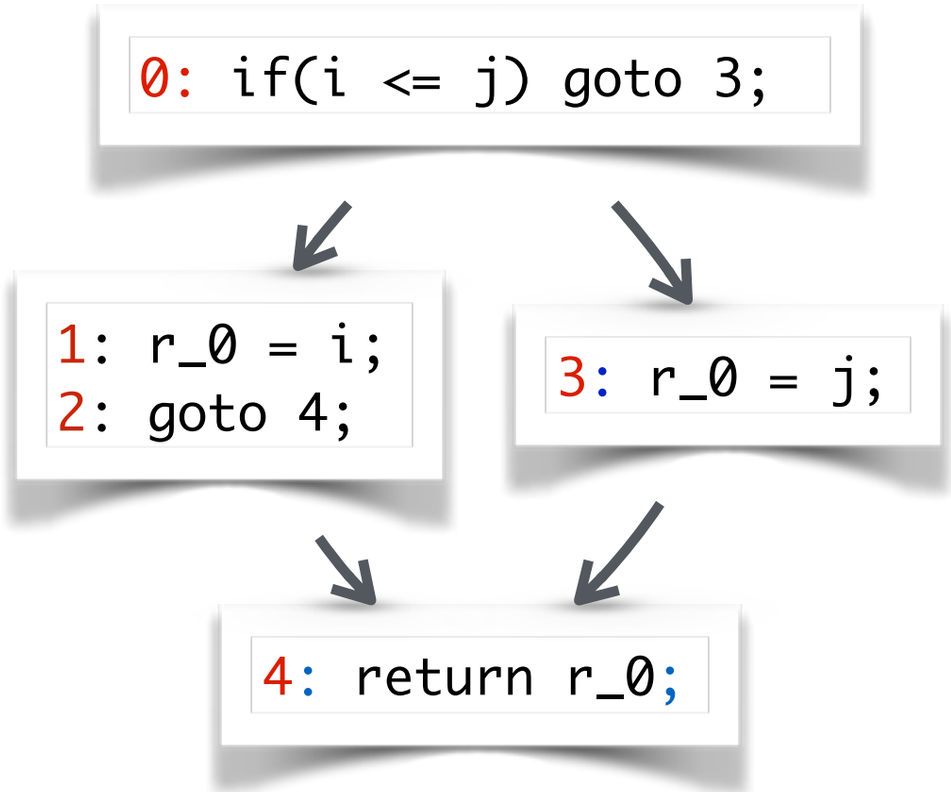
- The post-dominator tree is used, e.g., to determine control dependency.

Post-Dominator Tree

Java

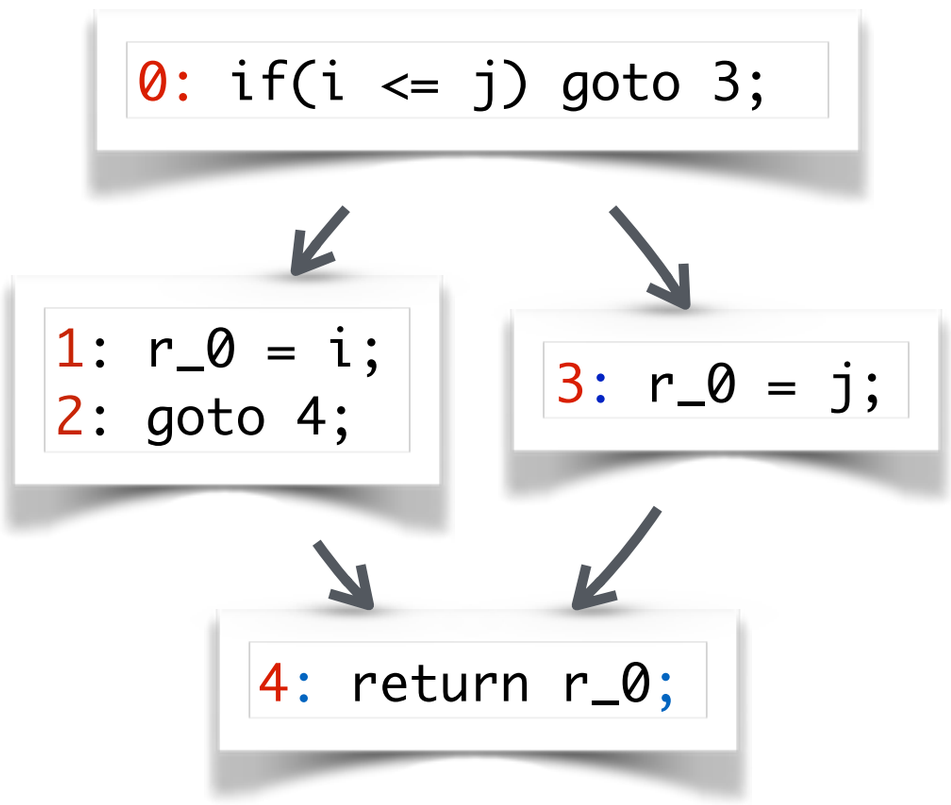
```
static int max(int i, int j) {
    int max;
    if (i > j)
        max = i;
    else
        max = j;
    return max;
}
```

CFG (3Address)

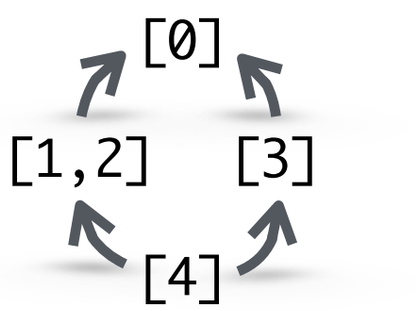


Post-Dominator Tree

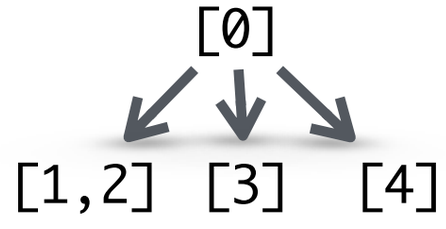
CFG (3Address)



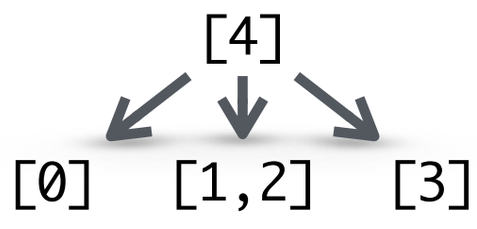
Reverse CFG



Dominator Tree



Post-Dominator Tree



Control-Dependence

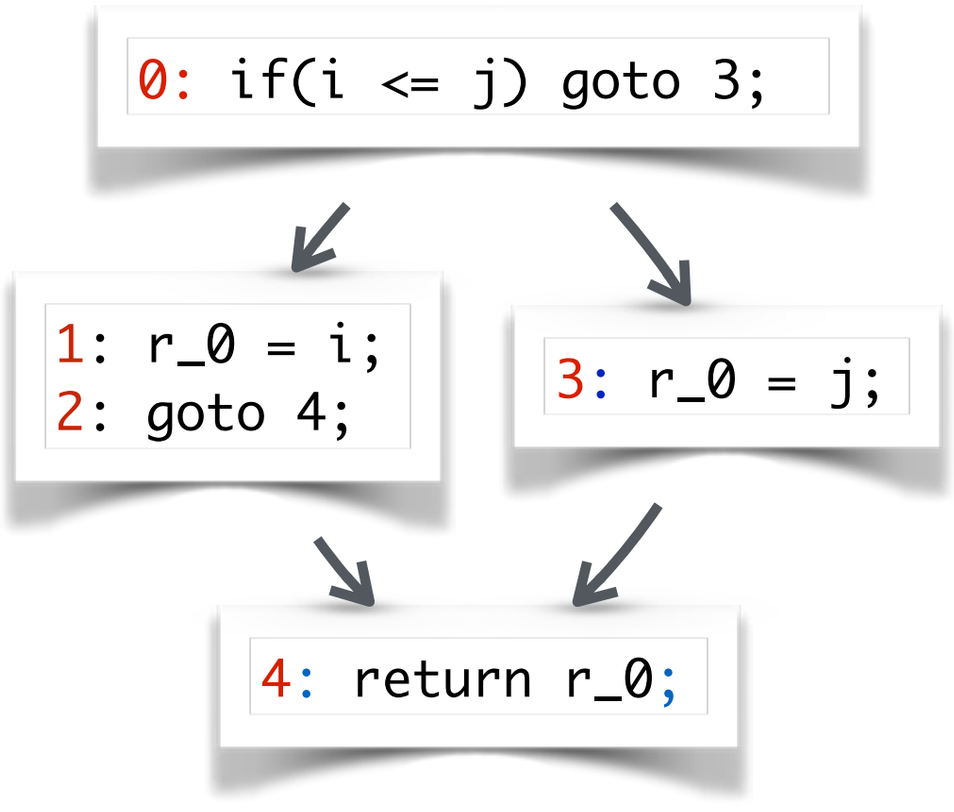
- An instruction/statement is control dependent on a predicate if the value of the predicate controls the execution of the instruction.

- Let G be a control flow graph; Let X and Y be nodes in G; Y is control dependent on X iff
  - there exists a directed path P from X to Y with any Z in P \ {X,Y} post-dominated by Y
  - X is not post-dominated by Y

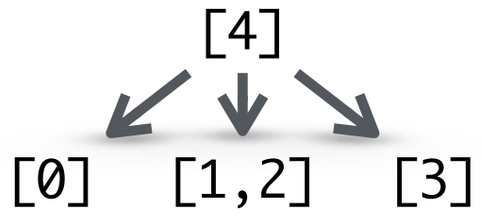
Control-Dependence

- An instruction/statement is control dependent on a predicate if the value of the predicate controls the execution of the instruction.

CFG (3Address)



Post Dominator Tree



Is [3] control dependent on [0]? Yes
Is [1,2] control dependent on [0]? Yes
Is [4] control dependent on [0]?
Is [4] control dependent on [1,2]?
Is [4] control dependent on [3]?

} No; [4] post dominates all other nodes

Identification of Lazily Initialized Fields

(,e.g. to facilitate the identification of immutable classes)

Control-Dependence

```
class S(final val i: Int, final val j : Int) {

    private[this] var hash: Int = _

    override def hashCode(): Int = {
        if (hash == 0) {
            hash = i*31+j
        }
        hash
    }
}
```

hash is updated if and only if **hash** still has the default value; after that hash is never updated again (unless the computation's result was the default value).

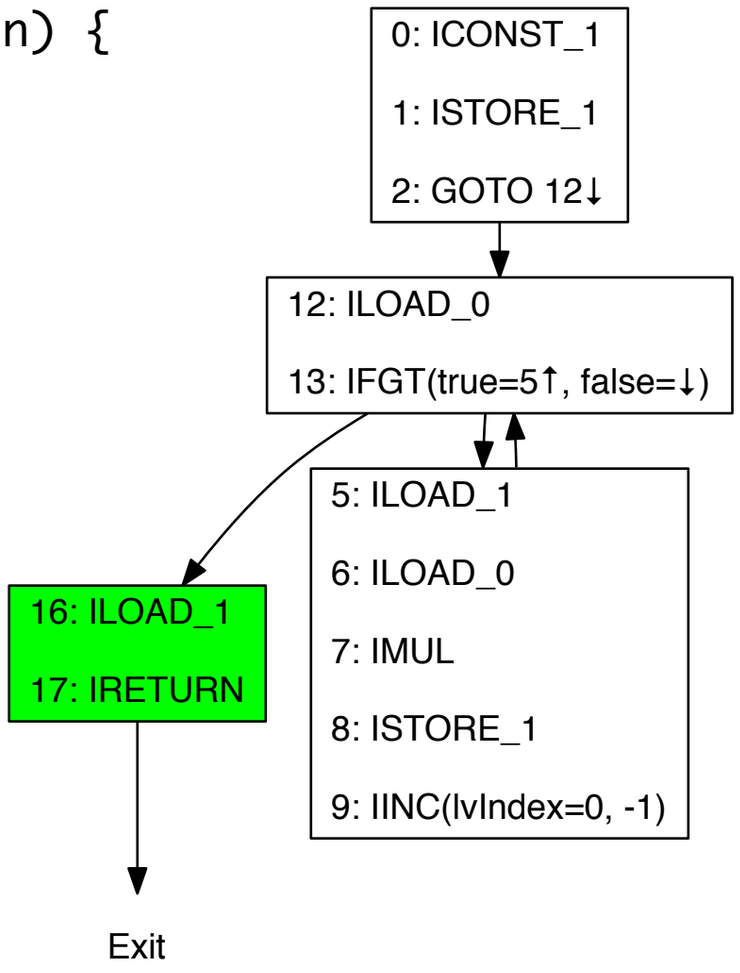
The update is thread-safe.

Def-Use Dependencies

Java

```
static int factorial(int n) {
    int r = 1;
    while (n > 0) {
        r *= n;
        n--;
    }
    return r;
}
```

CFG



Def-Use Information

PC	Instruction	Used By	Uses
0	iconst_1	{7,17}	
1	istore_1	*N/A*	
2	goto →12		
5	iload_1		
6	iload_0		
7	imul	{7,17}	1. Operand {-1,9} 2. Operand {0,7}
8	istore_1		
9	iinc (lv=0,val=-1)	{7,9,13}	
12	iload_0		
13	ifgt →5		{-1,9}
16	iload_1		
17	ireturn		{0,7}

Here “-1” is used to indicate a usage of the first parameter.

Loops - Def-Use Dependencies

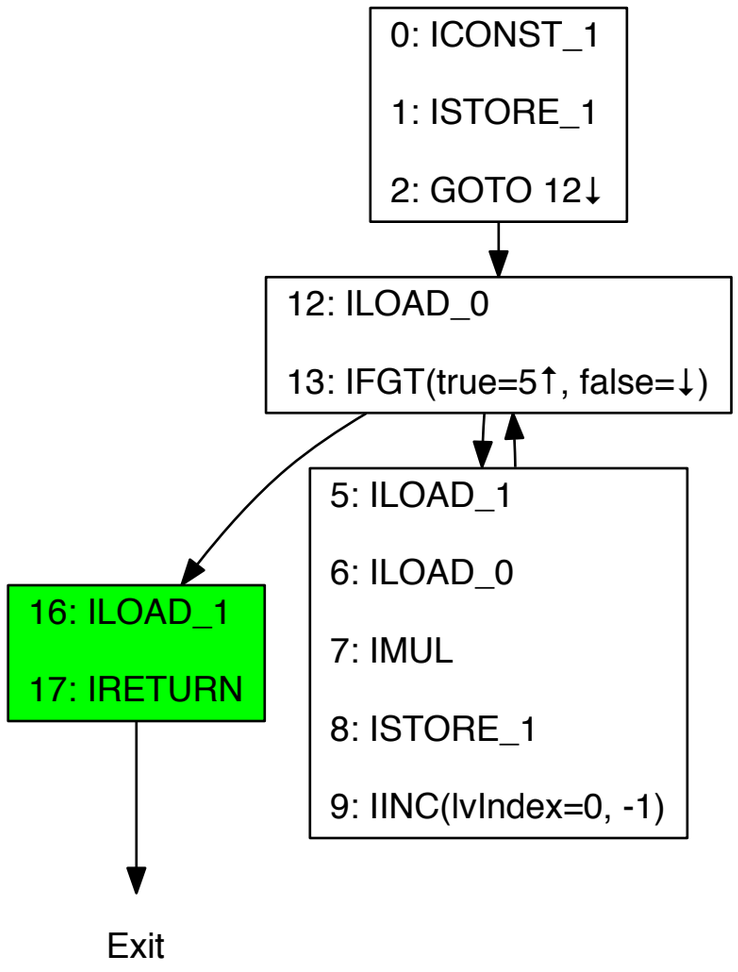
Java

```
static int factorial(int n) {
    int r = 1;
    while (n > 0) {
        r *= n;
        n--;
    }
    return r;
}
```

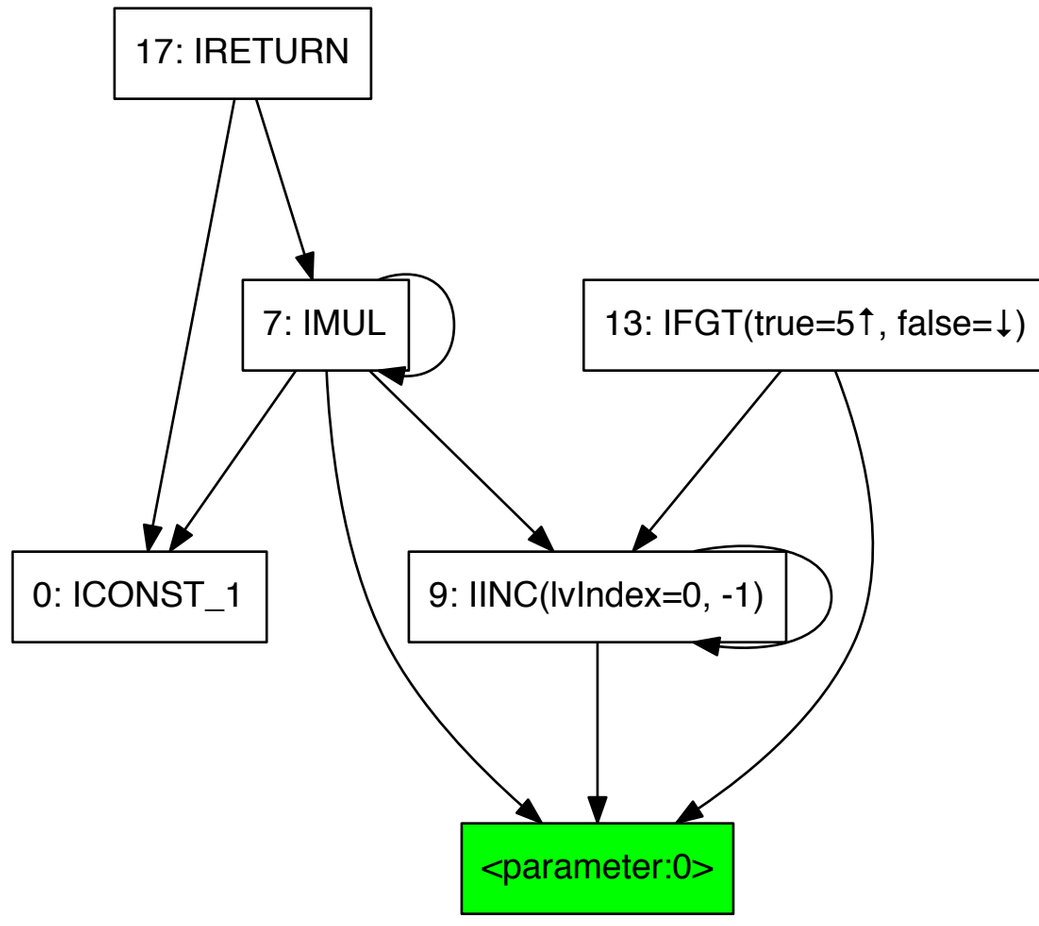
Bytecode

PC	Instruction
0	iconst_1
1	istore_1
2	goto →12
5	iload_1
6	iload_0
7	imul
8	istore_1
9	iinc (lv=0,val=-1)
12	iload_0
13	ifgt →5
16	iload_1
17	ireturn

CFG



Implicit Def-Use dependencies at the level of instructions.
Here, an instruction depends on another instruction if it uses the result of the other instruction.



SSA Code
(Static Single Assignment (form))

- Motivation: Many analyses require def-use information. I.e., the information where a used local variable is defined or vice versa.

- In SSA form each variable *has only one static definition-site in the program text*.

- When two control-flow paths merge, a selector function ϕ is used that initializes the variable based on the control flow that was taken.

- SSA form facilitates data-flow analyses; e.g., facilitates the elimination of redundant loads and computations *across* basic block boundaries.

Java Bytecode vs. Three-Address Code vs. SSA

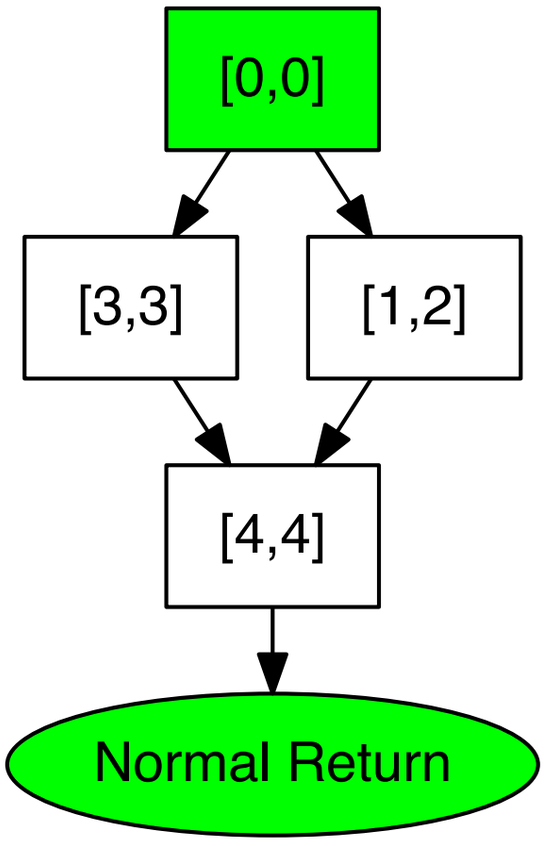
Java

```
static int max(int i, int j) {
    int max;
    if (i > j)
        max = i;
    else
        max = j;
    return max;
}
```

Three Address Code

```
0: if(i <= j) goto 3;
1: r_0 = i;
2: goto 4;
3: r_0 = j;
4: return r_0;
```

CFG



SSA

```
0: if(i <= j) goto 3;
```

```
3: t_1 = j;
```

```
1: t_2 = i;
2: goto 4;
```

```
t_3 = Φ(t_1,t_2)
4: return t_3;
```

Java Bytecode vs. Three-Address Code vs. SSA

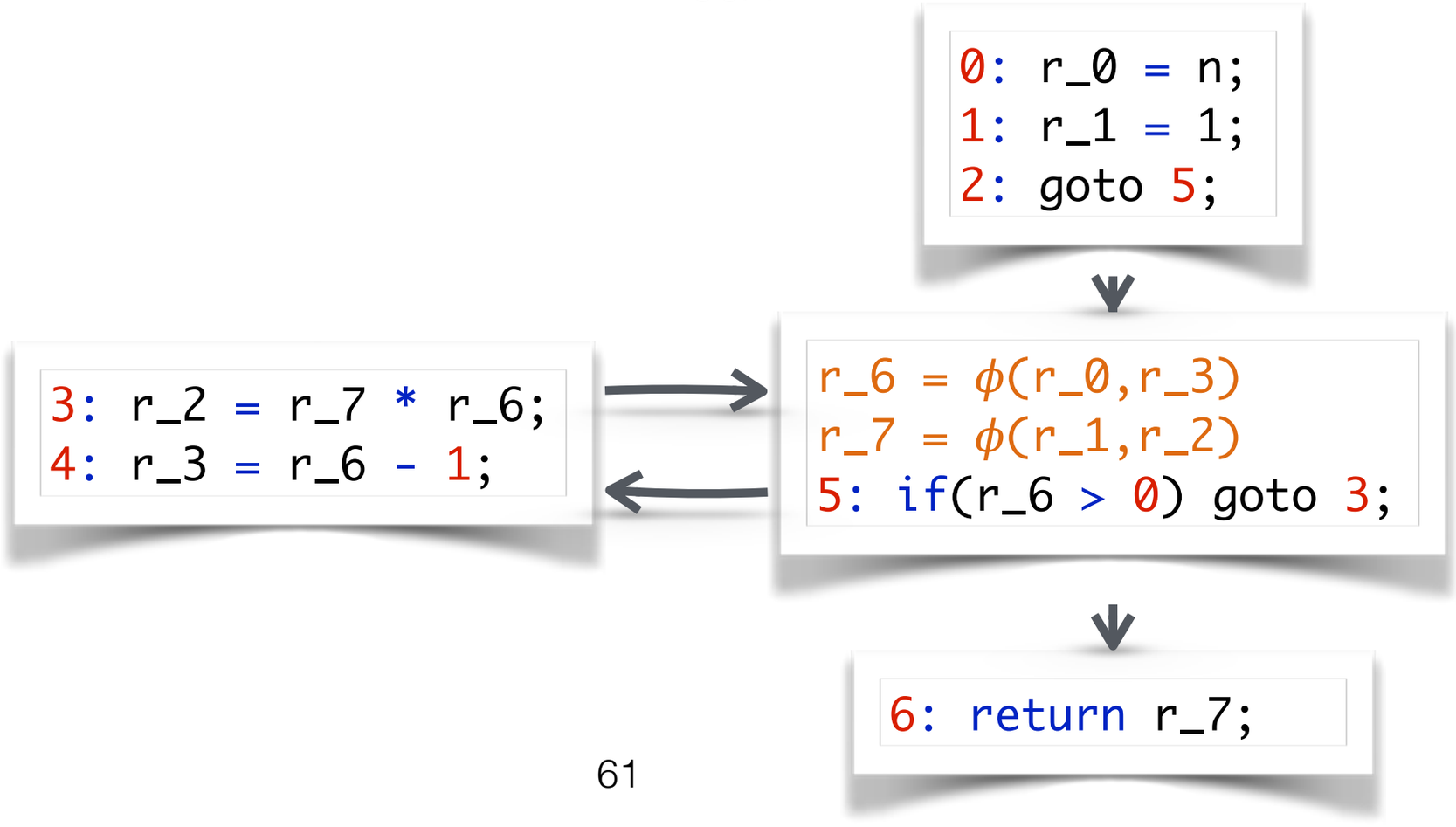
Java

```
static int factorial(int n) {
    int r = 1;
    while (n > 0) {
        r *= n;
        n--;
    }
    return r;
}
```

Three Address Code

```
0: r_0 = n;
1: r_1 = 1;
2: goto 5;
3: r_1 = r_1 * r_0;
4: r_0 = r_0 + -1;
5: if(r_0 > 0) goto 3;
6: return r_1;
```

SSA



Class Hierarchy

- A core data-structure which encodes the project's class hierarchy and which offers query functionality to get a type's supertypes and subtypes.

- In Java `java.lang.Object` is the super type of all types (including interface types). I.e., every interface (in the byte code explicitly) inherits from `Object`.

- In practice it is - when you want to analyze libraries - *basically always* the case that the class hierarchy contains "holes" (is not upwards closed).