Jikes Intermediate Code Representation

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Outline

- Jikes RVM Overview
- Intermediate Representation Overview
- Implementation
- Examples
  - Bytecode to HIR
  - HIR to LIR
  - LIR to MIR
  - MIR to Machine Code

Jikes RVM Overview

- Jikes Research Virtual Machine (Jikes RVM)
- Not a full JVM as it is missing libraries (AWT, Swing, J2EE)
- Implemented in the Java Programming Language
- Contains 3 compilers
  - Baseline: Generates code that is “obviously correct”
  - Optimizing: Applies a set of optimizations to a class when it is loaded at runtime
  - Adaptive: Methods are compiled with a non-optimizing compiler first and then selects “hot” methods for recompilation based on run-time profiling information.

Intermediate Representation Overview

- The Intermediate Representation (IR) used by Jikes is a register based IR
  - Allows more effective machine-specific optimizations
- An IR instruction is an N-tuple, consisting of an **operator** and some number of **operands**
  - An **Operator** is the instruction to perform
  - **Operands** are used to represent:
    - Symbolic Register
    - Physical Registers
    - Memory Locations
    - Constants
    - Branch targets
    - Method Signatures
    - Types
    - etc

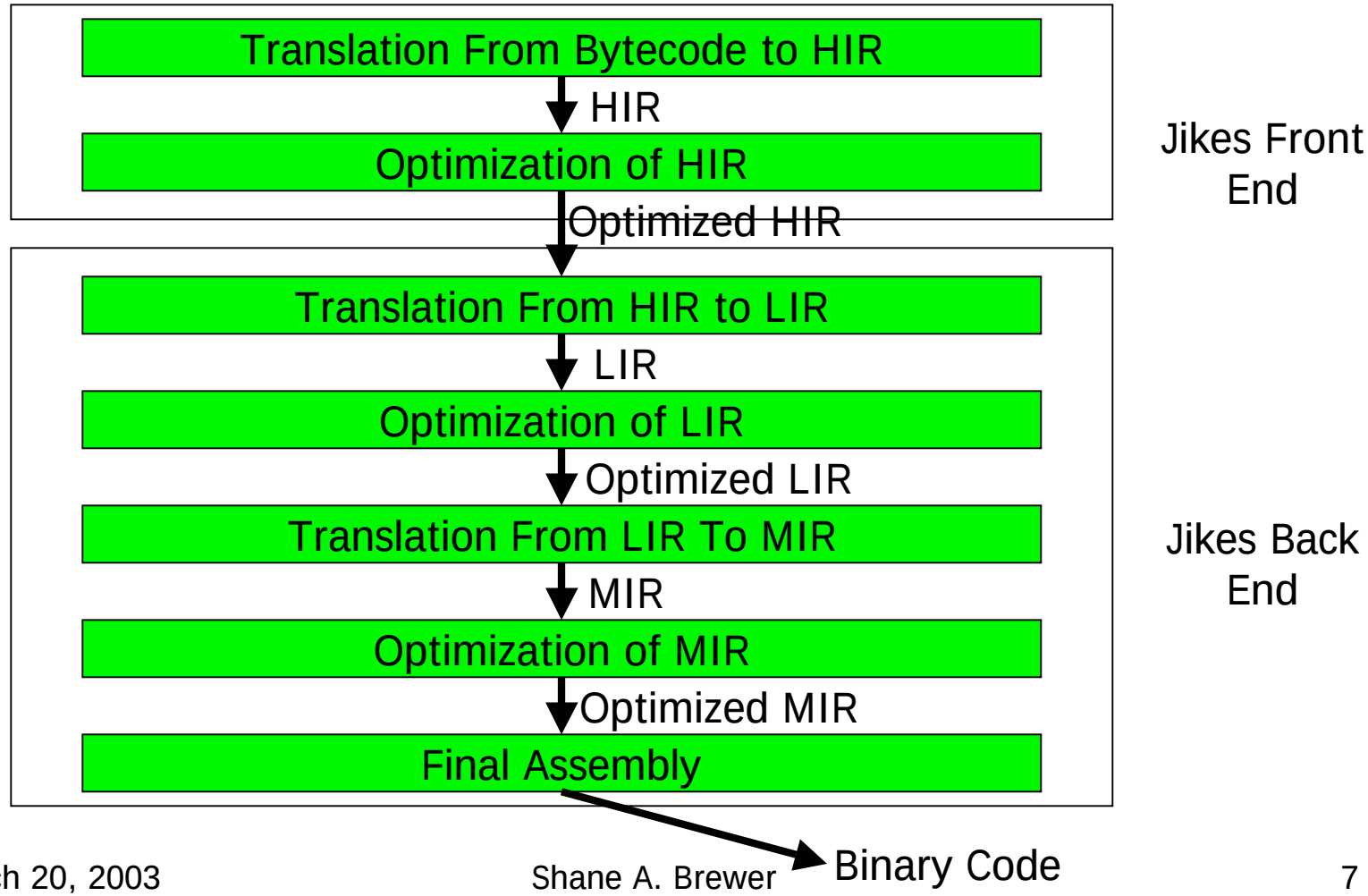
IR Overview

- Java type information preserved
- Java specific operators and optimizations
- Also include space for caching of optional auxiliary information such as:
  - Reaching definition sets
  - Dependence Graphs
  - Encoding of loop-nesting structure.

Levels of IR

- 3 levels of IR
  - HIR (High Level IR)
    - Operators similar to Java bytecode
      - Example: ARRAYLENGTH, NEW, GETFIELD, BOUNDS_CHECK, NULL_CHECK
    - Operate on symbolic registers instead of an implicit stack
    - Contains separate operators to implement explicit checks for run-time exceptions (eg., array-bounds checks)
  - LIR (Low Level IR)
    - Details of Jikes runtime and object layout
      - Example: GET_TIB (vtable), GET_JTOC (static), INT_LOAD (for getfield)
    - Expands complicated HIR structures such as TABLE_SWITCH
  - MIR (Machine Specific IR)
    - Similar to assembly code
    - Details of target architecture are introduced
    - Register Allocation is performed on MIR

IR Diagram


Translation From Bytecode to HIR
HIR
Optimization of HIR
Optimized HIR
Translation From HIR to LIR
LIR
Optimization of LIR
Optimized LIR
Translation From LIR To MIR
MIR
Optimization of MIR
Optimized MIR
Final Assembly
Binary Code
Jikes Front End
Jikes Back End

JTOC and TIB

- A TIB (Type Information Block) in Jikes included in an object header.
  - Is an array of Java object references
  - It's first component describes the object's class
  - The remaining components are compiled method bodies for the virtual methods of the class
  - Acts as the virtual method table
- The JTOC (Jalapeno Table of Contents) is an array that stores
  - all static fields
  - references to all static method bodies

Printing Out IR in Jikes

- To print out the Intermediate Representation produced by Jikes, the following command line options are available using the command
  -X:opt:<option>=true :
  - print_all_ir: Prints the IR after each compiler phase
  - high: Prints the IR after initial generation
  - final_hir: Prints the IR just before conversion to LIR
  - low: Prints the IR after conversion to LIR
  - final_lir: Prints the IR just before conversion to MIR
  - mir: Prints the IR after conversion to MIR
  - final_lir: Prints the IR just before conversion to machine code
  - mc: Prints the final machine code
  - cfg: Prints the control flow graph

Extended Basic Blocks [3]

- IR instructions are grouped into "Extended Basic Blocks"
- Method calls and potential trap sites do not end basic blocks
- Thus extra care is needed when performing data flow analysis or code motion
- Are constructed during translation from Java Bytecode to HIR

Extended Basic Block Example

Java Source

```
public Circle foo(Circle p, Circle[] a) {
  try {
    int n = Example.bar();
    p = Example.getNewCircle(a[n]);
  } catch (NullPointerException e) {
  ...
  } catch (Exception e) {
  ...
  } // End try-catch
  return p;
} // End method foo
```

Generic IR

```
        label          B0
1a:  PEI  call_static     n = Example.bar()
2a:  PEI  null_check      a
2b:  PEI  bounds_check a, n
2c:       ref_aload       t0 = @{a, n}
2d:  PEI  call_static     p = Example.getNewCircle(t0)
          end_block       B0

          label           B1
5a:       ref_return      p
          end_block       B1

(java.lang.NullPointerException handler)
          label           B2
3a:        ...
3b:       goto B1
          end_block       B2

(java.lang.Exeption handler)
          label           B3
4a:        ...
4b:       goto B1
          end_block       B3
```

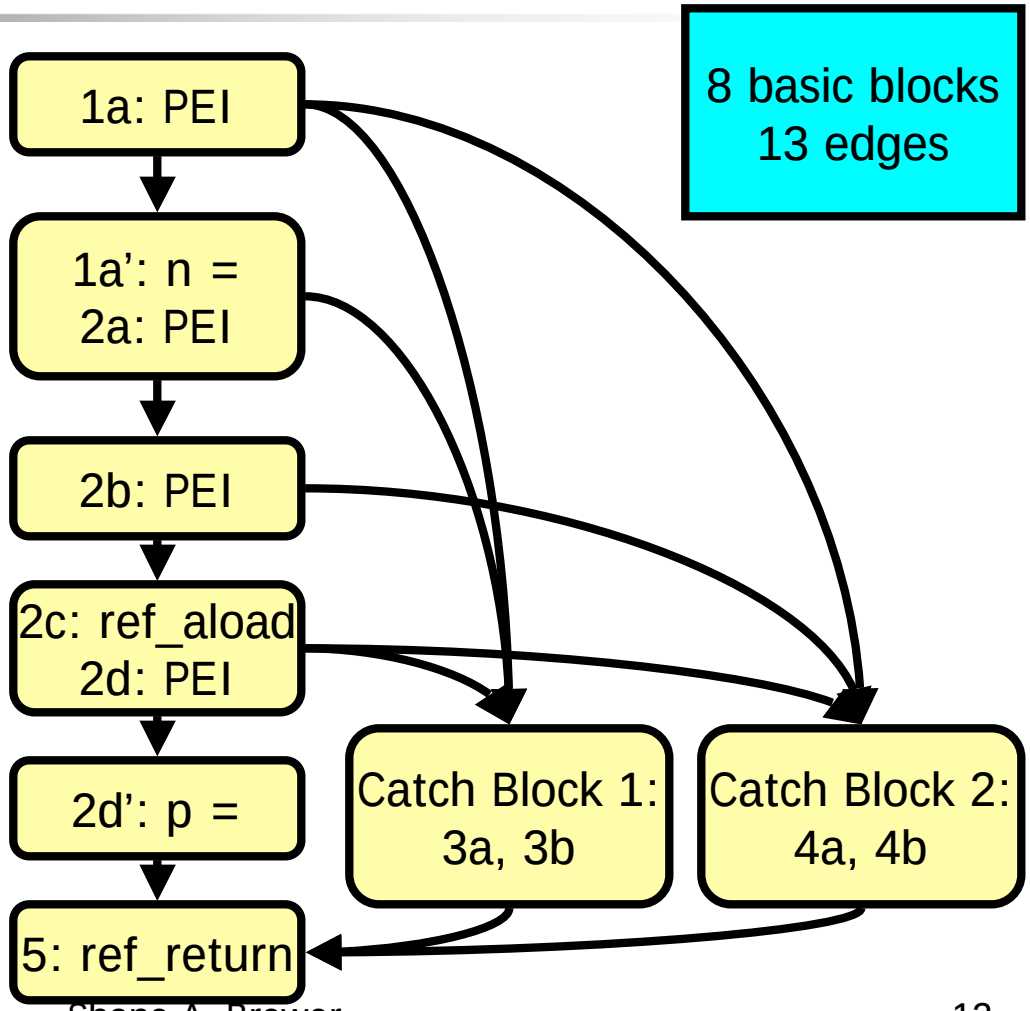
Extended Basic Block Example: Traditional Control Flow Graph

```
        label          B0
1a:  PEI  call_static     n = Example.bar()
2a:  PEI  null_check      a
2b:  PEI  bounds_check a, n
2c:       ref_aload       t0 = @{a, n}
2d:  PEI  call_static     p = Example.getNewCircle(t0)
          end_block       B0

          label           B1
5a:       ref_return      p
          end_block       B1

(java.lang.NullPointerException handler)
          label           B2
3a:         ...
3b:       goto B1
          end_block       B2

(java.lang.Exeption handler)
          label           B3
4a:         ...
4b:       goto B1
          end_block       B3
```



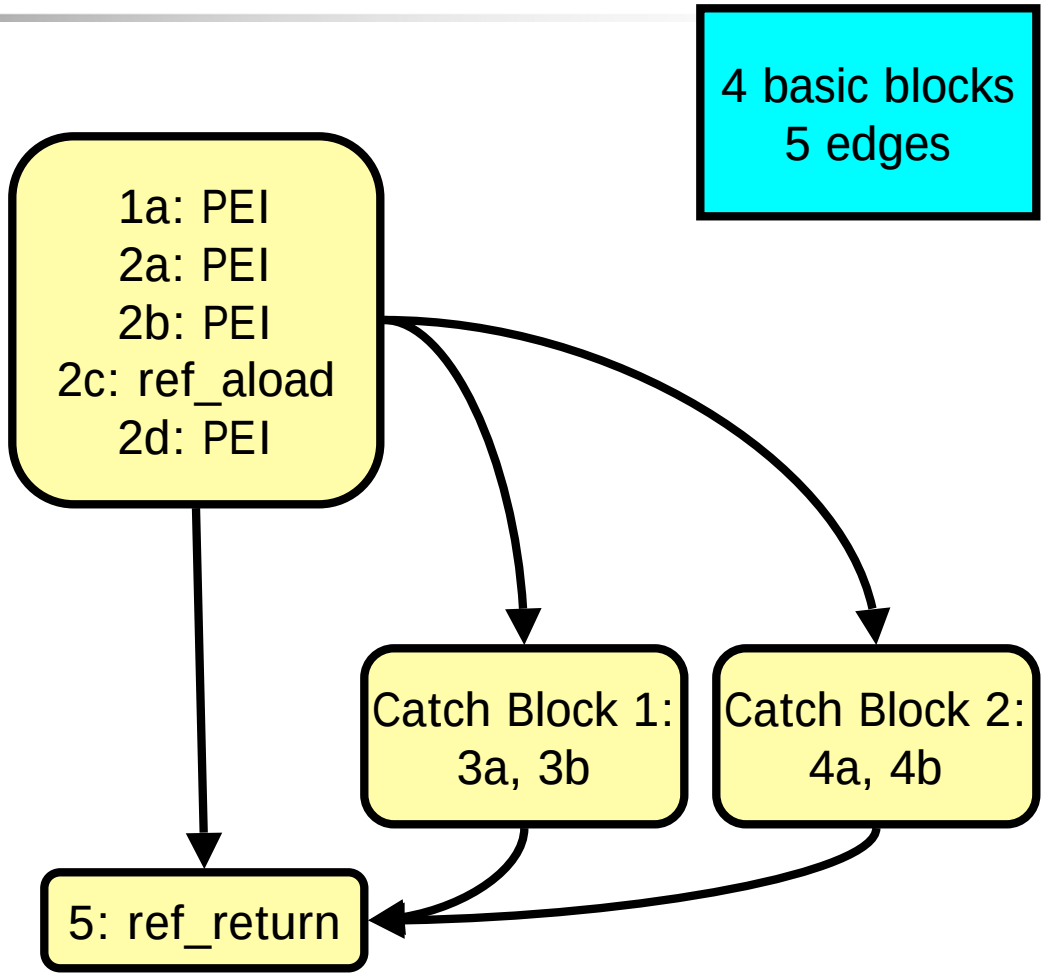
Extended Basic Block Example: Factored Control Flow Graph

```
        label          B0
1a:  PEI  call_static     n = Example.bar()
2a:  PEI  null_check      a
2b:  PEI  bounds_check a, n
2c:       ref_aload       t0 = @{a, n}
2d:  PEI  call_static     p = Example.getNewCircle(t0)
          end_block       B0

          label           B1
5a:       ref_return      p
          end_block       B1

(java.lang.NullPointerException handler)
          label           B2
3a:         ...
3b:       goto B1
          end_block       B2

(java.lang.Exeption handler)
          label           B3
4a:         ...
4b:       goto B1
          end_block       B3
```



Implementation

- Each IR operator is defined in the class OPT_Operators
  - OPT_Operators is automatically generated from a template by a driver
  - Driver takes 2 input files both named OperatorList.dat
    - /rvm/src/vm/compilers/optimizing/ir/instruction defines machine independent operators
    - /rvm/src/vm/arch/{arch}/compilers/optimizing/ir/instruction defines machine-dependent operators where {arch} specifies which architecture

OperatorList.dat File

- Each operator in OperatorList.dat is defined by a five-line record, consisting of:
  - SYMBOL: a static symbol to identify the operator
  - INSTRUCTION_FORMAT: The instruction format class that accepts this operator.
    - Every instance of OPT_Operator is assigned to exactly one Instruction Format class
    - Intended to represent the “syntactic form” of an instruction
  - TRAITS: A set of characteristics of the operator, composed with a bit-wise or (|) operator
  - IMPLDEFS: A set of registers implicitly defined by this operator; usually only for machine specific operators
  - IMPLUSES: A set of registers implicitly used by this operator; usually only for machine specific operators.

OperatorList.dat File Example

INT_ADD ← Integer Addition Operation

Binary ← Binary Instruction Format: 2 values and a return value

None ← No Traits

<blank line>

<blank line> ← No implicit uses or definitions

REF_IFCOMP ← Conditional branch operator based on values of 2 references

IfCmp ← IfCmp Instruction Format: 2 Values, Condition, Target, Branch Profile, Guard Result

Branch | conditional ← Branch and Conditional Traits

<blank line>

<blank line> ← No implicit uses or definitions

Addition Method Test Example: From Java Source To Java Bytecode

Java Source Code

```
class AdditionMethodTest {
  public static void main(String args[]) {
    int a = 3;
    int b = 4;
    int c = a + b;
    int d = getNewValue(c);
    return;
  } // End method main

  public static int getNewValue(int var) {
    return var * var;
  } // End method getNewValue
}
```

Java Bytecode

```
Method AdditionMethodTest()
  0 aload_0
  1 invokespecial #1 <Method java.lang.Object()>
  4 return
```

The aload_<n> loads the object stored in the local variable array at index n. The objectref is pushed on to the stack. In this case, the “this” object is pushed on to the stack.

Addition Method Test Example: From Java Source To Java Bytecode

Java Source Code

```
class AdditionMethodTest {
  public static void main(String args[]) {
    int a = 3;
    int b = 4;
    int c = a + b;
    int d = getNewValue(c);
    return;
  } // End method main

  public static int getNewValue(int var) {
    return var * var;
  } // End method getNewValue
}
```

Java Bytecode

```
Method AdditionMethodTest()
  0 aload_0
  1 invokespecial #1 <Method java.lang.Object()>
  4 return
```

The invokespecial bytecode calls the constructor of the “this” class’s superclass. In this case, the java.lang.Object is the superclass. No other bytecodes are present because

Addition Method Test Example: From Java Source To Java Bytecode

Java Source Code

```
class AdditionMethodTest {
  public static void main(String args[]) {
    int a = 3;
    int b = 4;
    int c = a + b;
    int d = getNewValue(c);
    return;
  } // End method main

  public static int getNewValue(int var) {
    return var * var;
  } // End method getNewValue
}
```

Java Bytecode

```
Method AdditionMethodTest()
  0 aload_0
  1 invokespecial #1 <Method java.lang.Object()>
  4 return
```

The return bytecode simple returns void

Addition Method Test Example: From Java Source To Java Bytecode

Java Source Code

```
class AdditionMethodTest {
  public static void main(String args[]) {
    int a = 3;
    int b = 4;
    int c = a + b;
    int d = getNewValue(c);
    return;
  } // End method main

  public static int getNewValue(int var) {
    return var * var;
  } // End method getNewValue
}
```

Java Bytecode

```
Method void main(java.lang.String[])
  0 iconst_3
  1 istore_1
  2 iconst_4
  3 istore_2
  4 iload_1
  5 iload_2
  6 iadd
  7 istore_3
  8 iload_3
  9 invokestatic #2 <Method int getNewValue(int)>
 12 istore 4
 14 return
```

The iconst_<n> bytecode loads the int constant onto the operand stack.

Addition Method Test Example: From Java Source To Java Bytecode

Java Source Code

```
class AdditionMethodTest {
  public static void main(String args[]) {
    int a = 3;
    int b = 4;
    int c = a + b;
    int d = getNewValue(c);
    return;
  } // End method main

  public static int getNewValue(int var) {
    return var * var;
  } // End method getNewValue
}
```

Java Bytecode

```
Method void main(java.lang.String[])
  0 iconst_3
  1 istore_1
  2 iconst_4
  3 istore_2
  4 iload_1
  5 iload_2
  6 iadd
  7 istore_3
  8 iload_3
  9 invokestatic #2 <Method int getNewValue(int)>
 12 istore 4
 14 return
```

The istore command stores the value on the top of the operand stack to the location in the local variable array location indicated by index.

Addition Method Test Example: From Java Source To Java Bytecode

Java Source Code

```
class AdditionMethodTest {
  public static void main(String args[]) {
    int a = 3;
    int b = 4;
    int c = a + b;
    int d = getNewValue(c);
    return;
  } // End method main

  public static int getNewValue(int var) {
    return var * var;
  } // End method getNewValue
}
```

Java Bytecode

```
Method void main(java.lang.String[])
  0 iconst_3
  1 istore_1
  2 iconst_4
  3 istore_2
  4 iload_1
  5 iload_2
  6 iadd
  7 istore_3
  8 iload_3
  9 invokestatic #2 <Method int getNewValue(int)>
 12 istore 4
 14 return
```

The iload command loads the int value stored in the location indicated by index in the local variable array.

Addition Method Test Example: From Java Source To Java Bytecode

Java Source Code

```
class AdditionMethodTest {
  public static void main(String args[]) {
    int a = 3;
    int b = 4;
    int c = a + b;
    int d = getNewValue(c);
    return;
  } // End method main

  public static int getNewValue(int var) {
    return var * var;
  } // End method getNewValue
}
```

Java Bytecode

```
Method void main(java.lang.String[])
   0 iconst_3
   1 istore_1
   2 iconst_4
   3 istore_2
   4 iload_1
   5 iload_2
   6 iadd
   7 istore_3
   8 iload_3
   9 invokestatic #2 <Method int getNewValue(int)>
  12 istore 4
  14 return
```

The iadd bytecode pops the top 2 int values off of the stack, performs the additions, and puts the result back on to the stack.

Addition Method Test Example: From Java Source To Java Bytecode

Java Source Code

```
class AdditionMethodTest {
  public static void main(String args[]) {
    int a = 3;
    int b = 4;
    int c = a + b;
    int d = getNewValue(c);
    return;
  } // End method main

  public static int getNewValue(int var) {
    return var * var;
  } // End method getNewValue
}
```

Java Bytecode

```
Method void main(java.lang.String[])
  0 iconst_3
  1 istore_1
  2 iconst_4
  3 istore_2
  4 iload_1
  5 iload_2
  6 iadd
  7 istore_3
  8 iload_3
  9 invokestatic #2 <Method int getNewValue(int)>
 12 istore 4
 14 return
```

The invokestatic bytecode invokes the static method getNewValue(). The method takes a single parameter which is pushed on the operand stack in the bytecode directly before.

Addition Method Test Example: From Java Source To Java Bytecode

Java Source Code

```
class AdditionMethodTest {
  public static void main(String args[]) {
    int a = 3;
    int b = 4;
    int c = a + b;
    int d = getNewValue(c);
    return;
  } // End method main

public static int getNewValue(int var) {
    return var * var;
  } // End method getNewValue
}
```

Java Bytecode

```
Method int getNewValue(int)
   0 iload_0
   1 iload_0
   2 imul
   3 ireturn
```

The imul bytecode is similar to the iadd bytecode except the product of the top 2 int values is pushed on to the operand stack.

Addition Method Test Example: From Java Source To Java Bytecode

Java Source Code

```
class AdditionMethodTest {
  public static void main(String args[]) {
    int a = 3;
    int b = 4;
    int c = a + b;
    int d = getNewValue(c);
    return;
  } // End method main

  public static int getNewValue(int var) {
    return var * var;
  } // End method getNewValue
}
```

Java Bytecode

```
Method int getNewValue(int)
   0 iload_0
   1 iload_0
   2 imul
   3 ireturn
```

The ireturn bytecode returns the int value that is stored on the top of the operand stack.

Conversion From Java Bytecode to HIR:

- Conversion from bytecode to HIR is performed by the compiler front-end
- The front-end contains 2 parts
  - The BC2IR algorithm that translates bytecodes to HIR and performs on-the-fly optimizations during translation
  - Additional optimizations perform on the HIR after translation.

The BC2IR translation

- Discovers extended-basic-blocks
- Constructs an exception-table for the method
- Creates HIR instructions for bytecodes
- Performs On-the-fly optimizations
  - Copy propagation
  - Constant propagation
  - Register renaming for local variables
  - Dead-Code elimination
  - Short final or static methods are inlined
- Even though these optimizations are performed in later phases, doing so here reduces the size of the HIR generated and thus compile time.

Example of On-the-Fly Analyses and Optimizations

- Consider Copy Propagation as an example:

Java Bytecode	Generated IR (optimization off)	Generated IR (optimization on)
iload x iconst 5 iadd istore y	INT_ADD tint, xint 5 INT_MOVE yint, tint	INT_ADD yint, xint, 5

AdditionTest Example: From Bytecode to HIR

Java Bytecode

```
Method AdditionMethodTest()
   0 aload_0
   1 invokespecial #1 <Method java.lang.Object()>
   4 return

Method void main(java.lang.String[])
   0 iconst_3
   1 istore_1
   2 iconst_4
   3 istore_2
   4 iload_1
   5 iload_2
   6 iadd
   7 istore_3
   8 iload_3
   9 invokestatic #2 <Method int getNewValue(int)>
  12 istore 4
  14 return

Method int getNewValue(int)
   0 iload_0
   1 iload_0
   2 imul
   3 ireturn
```

NOTE: This example was run with RVM command line option -X:opt:inline=false to prevent inlining

AdditionTest Example: From Bytecode to HIR

HIR

```
********* START OF IR DUMP  Initial HIR   FOR AdditionMethodTest.main ([Ljava/lang/String;)V
-13              LABEL0   Frequency:  0.0
-2             EG  ir_prologue          l0i([Ljava/lang/String;,d) =
1                int_move             l1i(B) = 3
3                int_move             l2i(B) = 4
7                int_move             l3i(B) = 7
9              EG  call               l5i(I) AF CF OF PF SF ZF = 66668, static"AdditionMethodTest.getNewValue (I)I", <unused>, 7
-3               return               <unused>
-1               bbend                BB0 (ENTRY)
*********   END OF IR DUMP  Initial HIR   FOR AdditionMethodTest.main ([Ljava/lang/String;)V
```

```
********* START OF IR DUMP  Initial HIR   FOR AdditionMethodTest.getNewValue (I)I
-13              LABEL0   Frequency:  0.0
-2             EG  ir_prologue          l0i(I,d) =
2                int_mul              t2i(I) = l0i(I,d), l0i(I,d)
3                int_move             t1i(I) = t2i(I)
-3               return               t1i(I)
-1               bbend                BB0 (ENTRY)
*********   END OF IR DUMP  Initial HIR   FOR AdditionMethodTest.getNewValue (I)I
```

Breakdown of the HIR

Java Bytecode

```
Method void main(java.lang.String[])
  0 iconst_3
  1 istore_1
  2 iconst_4
  3 istore_2
  4 iload_1
  5 iload_2
  6 iadd
  7 istore_3
  8 iload_3
  9 invokestatic #2 <Method int getNewValue(int)>
 12 istore 4
 14 return
```

HIR

-13 LABEL0 Frequency: 0.0

Each label is the beginning of a new Extended Basic Block

Is the corresponding line number in the source code, similar to what javap –c would print out. Some values have a negative number because they were inserted at a lower level as thus do not have a equivalent in the bytecode.

The Frequency is used by Jikes to predict control flow

Breakdown of the HIR

Java Bytecode

```
Method void main(java.lang.String[])
   0 iconst_3
   1 istore_1
   2 iconst_4
   3 istore_2
   4 iload_1
   5 iload_2
   6 iadd
   7 istore_3
   8 iload_3
   9 invokestatic #2 <Method int getNewValue(int)>
  12 istore 4
  14 return
```

HIR

-2 EG ir_prologue l0i([Ljava/lang/String;,d) =

Loads a pointer to the command line parameters (Array of String Objects) into local register 0 (discussed next)

Operator that have been defined in OperatorList.dat
ir_prologue is a pseudo instruction to represent the prologue

The E refers to that this line can produce an Exception
The G denotes that this line may yield to the Garbage Collector

Breakdown of the HIR

Java Bytecode

```
Method void main(java.lang.String[])
  0 iconst_3
  1 istore_1
  2 iconst_4
  3 istore_2
  4 iload_1
  5 iload_2
  6 iadd
  7 istore_3
  8 iload_3
  9 invokestatic #2 <Method int getNewValue(int)>
 12 istore 4
 14 return
```

Corresponds to line 1 in the main method source code

HIR

1

int_move

l1i(B) = 3

Operator to move an integer into a register

Breakdown of the HIR

Java Bytecode

```
Method void main(java.lang.String[])
  0 iconst_3
  1 istore_1
  2 iconst_4
  3 istore_2
  4 iload_1
  5 iload_2
  6 iadd
  7 istore_3
  8 iload_3
  9 invokestatic #2 <Method int getNewValue(int)>
 12 istore 4
 14 return
```

HIR

1 int_move l1i(B) = 3

The parameter indicates the type of the variable (taken from the JVM Specification)

B = Byte
C = Char
D = Double
F = Float
I = Int
J = Long
L<classname> = Reference
S = Short
Z = Boolean
[= Reference (One Array Dimension)

The suffix indicates the type of the register

i = Integer
c = Condition
d = Double
f = Float
l = Long
v = Validation

The prefix indicates the locality of the variable while the number indicates the register name

l = local
t = temporary

Breakdown of the HIR

Java Bytecode

```
Method void main(java.lang.String[])
  0 iconst_3
  1 istore_1
  2 iconst_4
  3 istore_2
  4 iload_1
  5 iload_2
  6 iadd
  7 istore_3
  8 iload_3
  9 invokestatic #2 <Method int getNewValue(int)>
 12 istore 4
 14 return
```

HIR

3 int_move I2i(B) = 4

Same idea as the last operator

Value we are assigning to the register

Breakdown of the HIR

Java Bytecode

```
Method void main(java.lang.String[])
  0 iconst_3
  1 istore_1
  2 iconst_4
  3 istore_2
  4 iload_1
  5 iload_2
  6 iadd
  7 istore_3
  8 iload_3
  9 invokestatic #2 <Method int getNewValue(int)>
 12 istore 4
 14 return
```

HIR

7	int_move	l3i(B) = 7

Same idea as the last operator

Breakdown of the HIR

Java Bytecode

```
Method void main(java.lang.String[])
  0 iconst_3
  1 istore_1
  2 iconst_4
  3 istore_2
  4 iload_1
  5 iload_2
  6 iadd
  7 istore_3
  8 iload_3
  9 invokestatic #2 <Method int getNewValue(int)>
 12 istore 4
 14 return
```

HIR

```
9     EG  call                    I5i(I) AF CF OF PF SF ZF = 66668,
 static"AdditionMethodTest.getNewValue (I)I", <unused>, 7
```

A call instruction

Indicates that the call can set the following EFLAGS on the IA32 architecture

A = Alignment
C = Carry
O = Overflow
P = Parity
S = Sign
Z = Zero

The name of the method we are calling. In this case it is to a static method called "AdditionMethodTest.getNewValue()"

Indicates that we have one parameter to the method, which is an integer (Again taken from the JVM Specification)

The offset into the JTOC which contains the address of the method

Breakdown of the HIR

Java Bytecode

```
Method void main(java.lang.String[])
  0 iconst_3
  1 istore_1
  2 iconst_4
  3 istore_2
  4 iload_1
  5 iload_2
  6 iadd
  7 istore_3
  8 iload_3
  9 invokestatic #2 <Method int getNewValue(int)>
 12 istore 4
 14 return
```

HIR

```
9     EG  call                    I5i(I) AF CF OF PF SF ZF = 66668,
 static"AdditionMethodTest.getNewValue (I)I", <unused>, 7
```

Indicates the return type of the method. In this case, the method returns an int (Taken from the JVM Specification)

Used if we are passing a guard to a method. In this case, no guard is passed.

The parameter that we are passing to the method. In this case, the int 7.

Breakdown of the HIR

Java Bytecode

```
Method void main(java.lang.String[])
  0 iconst_3
  1 istore_1
  2 iconst_4
  3 istore_2
  4 iload_1
  5 iload_2
  6 iadd
  7 istore_3
  8 iload_3
  9 invokestatic #2 <Method int getNewValue(int)>
 12 istore 4
 14 return
```

HIR

-3 return <unused>

Return instruction. No value is returned in this case.

Breakdown of the HIR

Java Source Code

```
public static int getNewValue(int var) {
    return var * var;
  } // End method getNewValue
}
```

Java Bytecode

```
Method int getNewValue(int)
   0 iload_0
   1 iload_0
   2 imul
   3 ireturn
```

HIR

```
-13     LABEL0   Frequency:  0.0
-2   EG  ir_prologue          l0i(I,d) =
2       int_mul              t2i(I) = l0i(I,d), l0i(I,d)
3       int_move              t1i(I) = t2i(I)
-3      return               t1i(I)
-1      bbend                 BB0 (ENTRY)
```

Same as described before except for one attribute.
In the use of l0i(I,d), the additional attribute describes the variable as one of the following:

x – Is Extant
d – Is Declared Type
p – Is Precise Type
+ - Is Positive Int

Breakdown of the HIR

Java Source Code

```
public static int getNewValue(int var) {
    return var * var;
  } // End method getNewValue
}
```

Java Bytecode

```
Method int getNewValue(int)
   0 iload_0
   1 iload_0
   2 imul
   3 ireturn
```

HIR

```
-13     LABEL0   Frequency:  0.0
-2   EG  ir_prologue          l0i(I,d) =
2       int_mul              t2i(I) = l0i(I,d), l0i(I,d)
3       int_move              t1i(I) = t2i(I)
-3      return               t1i(I)
-1      bbend                BB0 (ENTRY)
```

Multiplies the value stored in l0i (the first parameter passed to the method) to itself and stores the result in a temporary register t2i. The int_move instruction moves the calculated value from t2i to t1i

Breakdown of the HIR

Java Source Code

```
public static int getNewValue(int var) {
    return var * var;
  } // End method getNewValue
}
```

Java Bytecode

```
Method int getNewValue(int)
   0 iload_0
   1 iload_0
   2 imul
   3 ireturn
```

HIR

```
-13     LABEL0   Frequency:  0.0
-2   EG  ir_prologue          l0i(I,d) =
2       int_mul              t2i(I) = l0i(I,d), l0i(I,d)
3       int_move             t1i(I) = t2i(I)
-3      return               t1i(I)
-1      bbend                BB0 (ENTRY)
```

Returns the value stored in temporary register t1i.
bbend indicates the end of Extended Basic Block BB0

Optimization of HIR

- Simple optimization algorithms with modest compile-time overheads are performed.
- Generally fall into 3 classes:
  - Local Optimizations
    - Common Sub-expression elimination
    - Removal of redundant exception checks
    - Redundant load elimination
  - Flow-insensitive Optimizations
    - Copy Propagation
    - Dead code elimination
    - Conservative Escape Analysis
  - In-line Expansion of Method Calls
    - Guarded Receiver type prediction

Conversion From HIR to LIR

- The LIR expands the HIR instructions into operations that are specific to the Jikes RVM
  - Object Layout
  - Parameter-passing mechanisms
- Instructions like a single HIR “invokevirtual” instruction are expanded to 3 LIR instructions that:
  - Obtain the TIB pointer from an object
  - Obtain the address of the appropriate method body from the TIB
  - Transfer control to the method body
- A Dependence Graph is constructed for each extended basic block and includes the representation of:
  - True/Anti/Output Dependences for both Registers and Memory
  - Control/Synchronization/Exception Dependences
- LIR can be 2 to 3 times larger than corresponding HIR

AdditionTest Example: From HIR to LIR

HIR

```
********* START OF IR DUMP  Initial HIR   FOR AdditionMethodTest.main ([Ljava/lang/String;)V
-13              LABEL0   Frequency:  0.0
-2             EG  ir_prologue          l0i([Ljava/lang/String;,d) =
1                int_move             l1i(B) = 3
3                int_move             l2i(B) = 4
7                int_move             l3i(B) = 7
9              EG  call               l5i(I) AF CF OF PF SF ZF = 66668, static"AdditionMethodTest.getNewValue (I)I", <unused>, 7
-3               return               <unused>
-1               bbend                BB0 (ENTRY)
*********   END OF IR DUMP  Initial HIR   FOR AdditionMethodTest.main ([Ljava/lang/String;)V
```

LIR

```
********* START OF IR DUMP  Initial LIR   FOR AdditionMethodTest.main ([Ljava/lang/String;)V
-13              LABEL0   Frequency:  1.0
-2             EG  ir_prologue          l0si([Ljava/lang/String;,d) =
0               G  yieldpoint_prologue
9                ref_load             t6i([B) = 1124073932, 66668, <unused>, <unused>
9              EG  call               l5si(I) AF CF OF PF SF ZF = t6i([B), static"AdditionMethodTest.getNewValue (I)I", <unused>, 7
-3               return               <unused>
-1               bbend                BB0 (ENTRY)
*********   END OF IR DUMP  Initial LIR   FOR AdditionMethodTest.main ([Ljava/lang/String;)V
```

Breakdown of the LIR

HIR

```
-13        LABEL0   Frequency:  0.0
-2       EG  ir_prologue        l0i([Ljava/lang/String;,d) =
```

LIR

```
-13        LABEL0   Frequency:  1.0
-2       EG  ir_prologue        l0si([Ljava/lang/String;,d) =
```

l0i has changed to losi to indicate that the register is being used by SSA

Frequency has changed from 0.0 to 1.0, indicating that this Extended Basic Block has a high probability of being executed.

Breakdown of the LIR

HIR

```
1   int_move    I1i(B) = 3
3   int_move    I2i(B) = 4
7   int_move    I3i(B) = 7
9   EG  call    I5i(I) AF CF OF PF SF ZF = 66668, static"AdditionMethodTest.getNewValue (I)I", <unused>, 7
```

LIR

```
9   ref_load    t6i([B) = 1124073932, 66668, <unused>, <unused>
9   EG  call    I5si(I) AF CF OF PF SF ZF = t6i([B), static"AdditionMethodTest.getNewValue (I)I", <unused>, 7
```

All 3 int_move instructions have been replaced by a ref_load instruction, which obtains an array of bytes that refer to the address of the method.

1124073932 refers to the address of the JTOC

66668 is the offset into the JTOC that contains the address of the method

The call instruction now takes the temporary register t6i instead of the offset into the JTOC.

Breakdown of the LIR

HIR

```
-3      return          <unused>
-1      bbend            BB0 (ENTRY)
```

LIR

```
-3      return          <unused>
-1      bbend            BB0 (ENTRY)
```

No Change

AdditionTest Example: From HIR to LIR

HIR

```
********* START OF IR DUMP  Initial HIR   FOR AdditionMethodTest.getNewValue (I)I
-13              LABEL0   Frequency:  0.0
-2             EG  ir_prologue          l0i(I,d) =
2                int_mul              t2i(I) = l0i(I,d), l0i(I,d)
3                int_move              t1i(I) = t2i(I)
-3               return               t1i(I)
-1               bbend                BB0 (ENTRY)
*********   END OF IR DUMP  Initial HIR   FOR AdditionMethodTest.getNewValue (I)I
```

LIR

```
********* START OF IR DUMP  Initial LIR   FOR AdditionMethodTest.getNewValue (I)I
-13              LABEL0   Frequency:  1.0
-2             EG  ir_prologue          l0si(I,d) =
0               G  yieldpoint_prologue
2                int_mul              t2si(I) = l0si(I,d), l0si(I,d)
-3               return               t2si(I)
-1               bbend                BB0 (ENTRY)
*********   END OF IR DUMP  Initial LIR   FOR AdditionMethodTest.getNewValue (I)I
```

Breakdown of the LIR

HIR

```
-13     LABEL0   Frequency:  0.0
-2   EG  ir_prologue          l0i(I,d) =
```

LIR

```
-13     LABEL0   Frequency:  1.0
-2   EG  ir_prologue          l0si(I,d) =
```

Same as described before

Breakdown of the LIR

HIR

```
2     int_mul     t2i(I) = I0i(I,d), I0i(I,d)
3     int_move     t1i(I) = t2i(I)
-3    return      t1i(I)
-1    bbend       BB0 (ENTRY)
```

LIR

```
2     int_mul     t2si(I) = I0si(I,d), I0si(I,d)
-3    return      t2si(I)
-1    bbend       BB0 (ENTRY)
```

Here we see that we have optimized out the int_move instruction and just return the value in temporary register t2si

Optimizations of LIR

- Local common Subexpression elimination is the only optimization performed on LIR
- In principle, any optimization performed on HIR could also be performed on LIR, but the size of LIR makes it not as attractive as HIR

Conversion From LIR to MIR

- Dependence Graphs for the extended basic blocks of a method partitioned into trees.
- These trees are fed into the Bottom-Up Rewriting System (BURS) which produces the MIR
- Symbolic registers are mapped to physical registers
- A **Prolog** is added at the beginning and an **Epilog** is added at the end of each method [2]

Method Prolog and Epilog [2]

- The method Prolog:
  - Saves any nonvolatile registers needed by the method
  - Checks to see if a yield has been requested
  - Locks the indicated object if the method is synchronized
  - Acts as a yield point
- The method Epilog:
  - Restores any saved registers
  - Deallocate the stack frame.
  - Unlocks the indicated object if the method is synchronized

AdditionTest Example: From LIR to MIR

LIR

```
********* START OF IR DUMP  Initial LIR   FOR AdditionMethodTest.main ([Ljava/lang/String;)V
-13                LABEL0   Frequency:  1.0
-2              EG  ir_prologue            l0si([Ljava/lang/String;,d) =
0                G  yieldpoint_prologue
9                  ref_load                t6i([B) = 1124073932, 66668, <unused>, <unused>
9               EG  call                   l5si(I) AF CF OF PF SF ZF = t6i([B), static"AdditionMethodTest.getNewValue (I)I", <unused>, 7
-3                 return                  <unused>
-1                 bbend                   BB0 (ENTRY)
*********   END OF IR DUMP  Initial LIR   FOR AdditionMethodTest.main ([Ljava/lang/String;)V
```

MIR

```
********* START OF IR DUMP  Initial MIR   FOR AdditionMethodTest.main ([Ljava/lang/String;)V
-13                LABEL0   Frequency:  1.0
-2              EG  ir_prologue            l0si([Ljava/lang/String;,d) =
0                G  yieldpoint_prologue
9               EG  ia32_call              l5si(I) AF CF OF PF SF ZF = <0+1124140600>DW, static"AdditionMethodTest.getNewValue (I)I",7
-3                 ia32_ret                <unused>, <unused>, <unused>
-1                 bbend                   BB0 (ENTRY)
*********   END OF IR DUMP  Initial MIR   FOR AdditionMethodTest.main ([Ljava/lang/String;)V
```

Breakdown of the MIR

LIR

```
-13     LABEL0   Frequency:  1.0
-2   EG  ir_prologue          l0si([Ljava/lang/String;,d) =
0     G  yieldpoint_prologue
```

MIR

```
-13     LABEL0   Frequency:  1.0
-2   EG  ir_prologue          l0si([Ljava/lang/String;,d) =
0     G  yieldpoint_prologue
```

No change

Breakdown of the MIR

LIR

```
9        ref_load      t6i([B) = 1124073932, 66668, <unused>, <unused>
9     EG  call         l5si(I) AF CF OF PF SF ZF = t6i([B), static"AdditionMethodTest.getNewValue (I)I", <unused>, 7
-3       return        <unused>
-1       bbend         BB0 (ENTRY)
```

MIR

```
9     EG  ia32_call    l5si(I) AF CF OF PF SF ZF = <0+1124140600>DW, static"AdditionMethodTest.getNewValue (I)I", 7
-3       ia32_ret      <unused>, <unused>, <unused>
-1       bbend         BB0 (ENTRY)
```

The IR instructions “call” and “return” have been replaced by the IA32 specific “ia32_call” and “ia32_ret” instructions.

The ref_load instruction has been replaced with a literal address (Not sure what DW means or why it is 0 +).

AdditionTest Example: From LIR to MIR

LIR

```
********* START OF IR DUMP  Initial LIR   FOR AdditionMethodTest.getNewValue (I)I
-13              LABEL0   Frequency:  1.0
-2             EG  ir_prologue          l0si(I,d) =
0               G  yieldpoint_prologue
2                int_mul              t2si(I) = l0si(I,d), l0si(I,d)
-3               return              t2si(I)
-1               bbend               BB0 (ENTRY)
*********  END OF IR DUMP  Initial LIR   FOR AdditionMethodTest.getNewValue (I)I
```

MIR

```
********* START OF IR DUMP  Initial MIR   FOR AdditionMethodTest.getNewValue (I)I
-13              LABEL0   Frequency:  1.0
-2             EG  ir_prologue          l0i(I,d) =
0               G  yieldpoint_prologue
2                ia32_imul2           l0i(I,d) AF CF OF PF SF ZF <-- l0i(I,d)
-3               ia32_ret            <unused>, l0i(I), <unused>
-1               bbend               BB0 (ENTRY)
*********  END OF IR DUMP  Initial MIR   FOR AdditionMethodTest.getNewValue (I)I
```

Breakdown of the MIR

LIR

```
-13     LABEL0   Frequency:  1.0
-2   EG  ir_prologue          l0si(I,d) =
0     G  yieldpoint_prologue
```

MIR

```
-13     LABEL0   Frequency:  1.0
-2   EG  ir_prologue          l0i(I,d) =
0     G  yieldpoint_prologue
```

No changes

Breakdown of the MIR

LIR

```
2     int_mul     t2si(I) = l0si(I,d), l0si(I,d)
-3    return      t2si(I)
-1    bbend       BB0 (ENTRY)
```

MIR

```
-2    ia32_imul2  l0i(I,d) AF CF OF PF SF ZF <-- l0i(I,d)
-3    ia32_ret    <unused>, l0i(I), <unused>
-1    bbend       BB0 (ENTRY)
```

The int_mul instruction is replaced with an ia32_imul2 instruction as the compiler knows that it is multiplying the same values together.

The temporary register t2si is also eliminated.

MIR Optimizations

- Live variable analysis is performed
- A Linear-scan global register-allocation algorithm assigns physical machine registers to symbolic MIR registers
  - Based on a greedy algorithm

Conversion From MIR to Machine Code

- The binary executable code is emitted into an array of ints that is the method body
- Finalizes the exception table
- Converts intermediate-instruction offsets into machine-code offsets.

AdditionTest Example: From MIR to IA32 Machine Code

```
-2    ia32_imul2    l0i(I,d) AF CF OF PF SF ZF <-- l0i(I,d)
-3    ia32_ret      <unused>, l0i(I), <unused>
-1    bbend         BB0 (ENTRY)
```

MIR

Machine Code

```
000000|  CMP      esp        -60[esi] | 3B66C4
000003|  JLE      21                  | 0F8E00000000
000009|  PUSH     -72[esi]            | FF76B8
00000C|  MOV      -72[esi]   esp      | 8966B8
00000F|  PUSH     9552                | 6850250000
000014|  ADD      esp        -4       | 83C4FC
000017|  CMP      -52[esi]   0        | 837ECC00
00001B|  JNE      25                  | 0F8500000000
000021|  MOV      eax        7        | B807000000
000026|  ADD      esp        -4       | 83C4FC
000029|  CALL     [43010638]          | FF1538060143
00002F|  ADD      esp        8        | 83C408
000032|  POP      -72[esi]            | 8F46B8
000035|  RET      4                   | C20400
000038| <<< 000003
000038|  INT      67                  | CD43
00003A|  JMP      9                   | EBCD
00003C| <<< 00001B
00003C|  CALL     [43002924]          | FF1524290043
000042|  JMP      33                  | EBDD
*********  END OF:  Final machine code  FOR AdditionMethodTest.main ([Ljava/lang/String;)V
```

Numbers on the right indicate IA32 opcodes

Numbers of the left indicate offsets in the method???

AdditionTest Example: From MIR to IA32 Machine Code

MIR

```
********* START OF IR DUMP  Initial MIR   FOR AdditionMethodTest.getNewValue (I)I
-13              LABEL0   Frequency:  1.0
-2             EG  ir_prologue          I0i(I,d) =
0               G  yieldpoint_prologue
2                ia32_imul2            I0i(I,d) AF CF OF PF SF ZF <-- I0i(I,d)
-3               ia32_ret              <unused>, I0i(I), <unused>
-1               bbend                 BB0 (ENTRY)
*********  END OF IR DUMP  Initial MIR   FOR AdditionMethodTest.getNewValue (I)I
```

Machine Code

```
000000|     IMUL              eax            eax  | 0FAFC0
000003|     RET                4                 | C20400
*********  END OF:  Final machine code   FOR AdditionMethodTest.getNewValue (I)I
```

References

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