Code Generation

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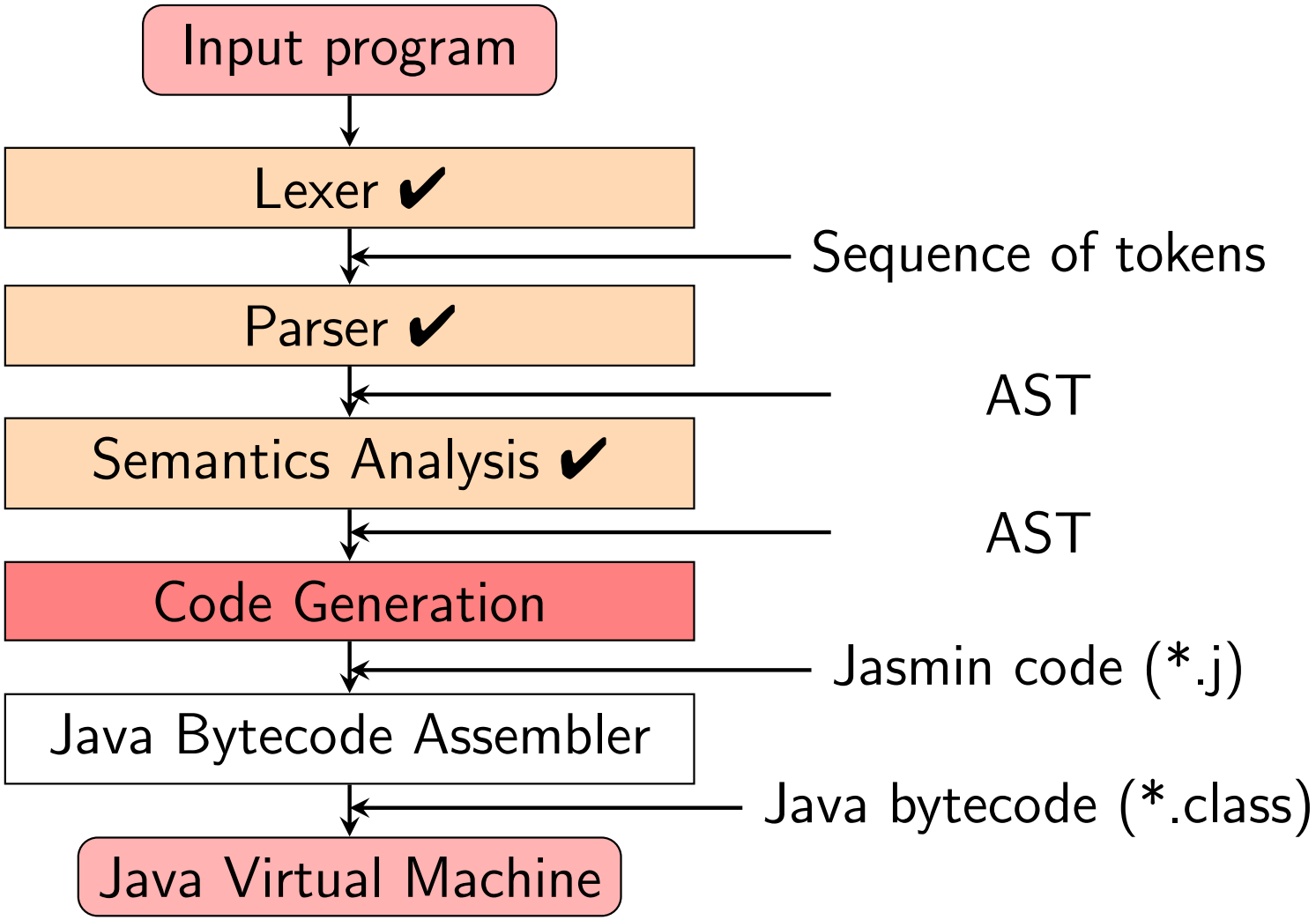
Outline

Our Compiler



Remind

What is the appropriate Java bytecode of the following expression?
a = b + 1 //Assume that a is allocated at index 1 and b at 2

A. iload_1
iload_2
iconst_1
iadd

B. iload_2
iconst_1
iadd
istore_1

C. iload_1
iconst_1
iadd
istore_2

D. istore_1
iload_2
iadd
iconst_1

BKOOL-Java mapping

- A source program $\Rightarrow$ Java class(es)
- A class $\Rightarrow$ a class
- An instance method $\Rightarrow$ an instance method
- A static method $\Rightarrow$ a static method
- A parameter $\Rightarrow$ a parameter
- A local variable $\Rightarrow$ a local variable
- An expression $\Rightarrow$ an expression
- A statement $\Rightarrow$ a statement
- An invocation $\Rightarrow$ an invocation

Some issues

- An array declaration $\Rightarrow$ a declaration + code
  - ◁ class field $\Rightarrow$code in a class init
  - ◁ instance field $\Rightarrow$code in an init
  - ◁ local $\Rightarrow$code in the enclosing method
- A main method $\Rightarrow$a main method with different signature
  - ◁ void static main() $\Rightarrow$public static void main(String [] args)

Example

```
class Main {
   a:integer;
   final integer b = 1;
   c:float[3];
   static d:float;

   void main() {
       d:float[3];
       x: Main;
       x := new Main();
       x.c[0] := d[0];
       while (x.a > 10) do {
           x.a := x.a + 1;
       }
   }
}
```

```
public class Main {
    protected int a;
    protected final int b = 1;
    protected float c[] = new float[3];
    public static float d;

    public static void main(String[] arg) {
        float d[] = new float[3];
        Main x = new Main()
        x.c[0] = d[0];
        while (x.a > 10) do {
            x.a = x.a + 1;
        }
      return ;
    }
}
```

Jasmin

- Java source code to Java byte code

```
javac -g <*.java>
```

  -g: to generate debug information

- Java byte code to Jasmin code

```
java -cp <pathTo bcel>/bcel.jar JasminVisitor <*.class>
```

  Read JavaToJasmin script for details

- Jasmin code to Java byte code

```
java  -jar <pathTo jasmin>/jasmin.jar <*.j>
```

  Read run script for details

Example-Jasmin

```
public class Main {
      protected int a;
      protected final int b = 1;
      protected float c[] =
                  new float[3];
      public static float d;
```

Example-Jasmin

```
public class Main {
      protected int a;
      protected final int b = 1;
      protected float c[] =
                  new float[3];
      public static float d;
```

```
.source Main.java
.class public Main
.super java/lang/Object
.field protected a I
.field protected final b I = 1
.field protected c [F
.field static public d F
```

Example-Jasmin

```
public class Main {
      protected int a;
      protected final int b = 1;
      protected float c[] =
                  new float[3];
      public static float d;
```

```
.source Main.java
.class public Main
.super java/lang/Object
.field protected a I
.field protected final b I = 1
.field protected c [F
.field static public d F
```

```
.method public <init>()V
.limit stack 2
.limit locals 1
.var 0 is this LMain; from Label0 to Label1
Label0: aload_0
        invokespecial java/lang/Object/<init>()V
        aload_0
        iconst_1
        putfield Main.b I
        aload_0
        iconst_3
        newarray float
        putfield Main.c [F
Label1: return
.end method
```

Example-Jasmin (cont'd)

```
public static void main
                (String[] arg) {
    float d[] = new float[3];
    Main x = new Main();
```

```
.method public static main
                ([Ljava/lang/String;)V
.limit stack 4
.limit locals 3
.var 0 is arg [Ljava/lang/String;
        from Label1 to Label2
.var 1 is d [F
        from Label3 to Label2
.var 2 is x LMain;
        from Label5 to Label2
```

Example-Jasmin (cont'd)

```
public static void main
                (String[] arg) {
    float d[] = new float[3];
    Main x = new Main();
```

```
.method public static main
                ([Ljava/lang/String;)V
.limit stack 4
.limit locals 3
.var 0 is arg [Ljava/lang/String;
        from Label1 to Label2
.var 1 is d [F
        from Label3 to Label2
.var 2 is x LMain;
        from Label5 to Label2
```

```
float d[] = new float[3];
```

```
iconst_3
newarray float
astore_1
```

Example-Jasmin (cont'd)

```
public static void main
                (String[] arg) {
    float d[] = new float[3];
    Main x = new Main();
```

```
.method public static main
                ([Ljava/lang/String;)V
.limit stack 4
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.var 0 is arg [Ljava/lang/String;
        from Label1 to Label2
.var 1 is d [F
        from Label3 to Label2
.var 2 is x LMain;
        from Label5 to Label2
```

```
float d[] = new float[3];
```

```
iconst_3
newarray float
astore_1
```

```
Main x = new Main();
```

```
new Main
dup
invokespecial Main/<init>()V
astore_2
```

Example-Jasmin (cont'd)

```
x.c[0] = d[0];
```

```
aload_2
getfield Main.c [F
iconst_0
aload_1
iconst_0
faload
fastore
```

Example-Jasmin (cont'd)

```
x.c[0] = d[0];
```

```
aload_2
getfield Main.c [F
iconst_0
aload_1
iconst_0
faload
fastore
```

```
while (x.a > 10) do {
    x.a = x.a + 1;
} ;
```

```
aload_2
getfield Main.a I
bipush 10
if_icmple Label0
aload_2
aload_2
getfield Main.a I
iconst_1
iadd
putfield Main.a I
Label0:
```

Example-Jasmin (cont'd)

```
x.c[0] = d[0];
```

```
aload_2
getfield Main.c [F
iconst_0
aload_1
iconst_0
faload
fastore
```

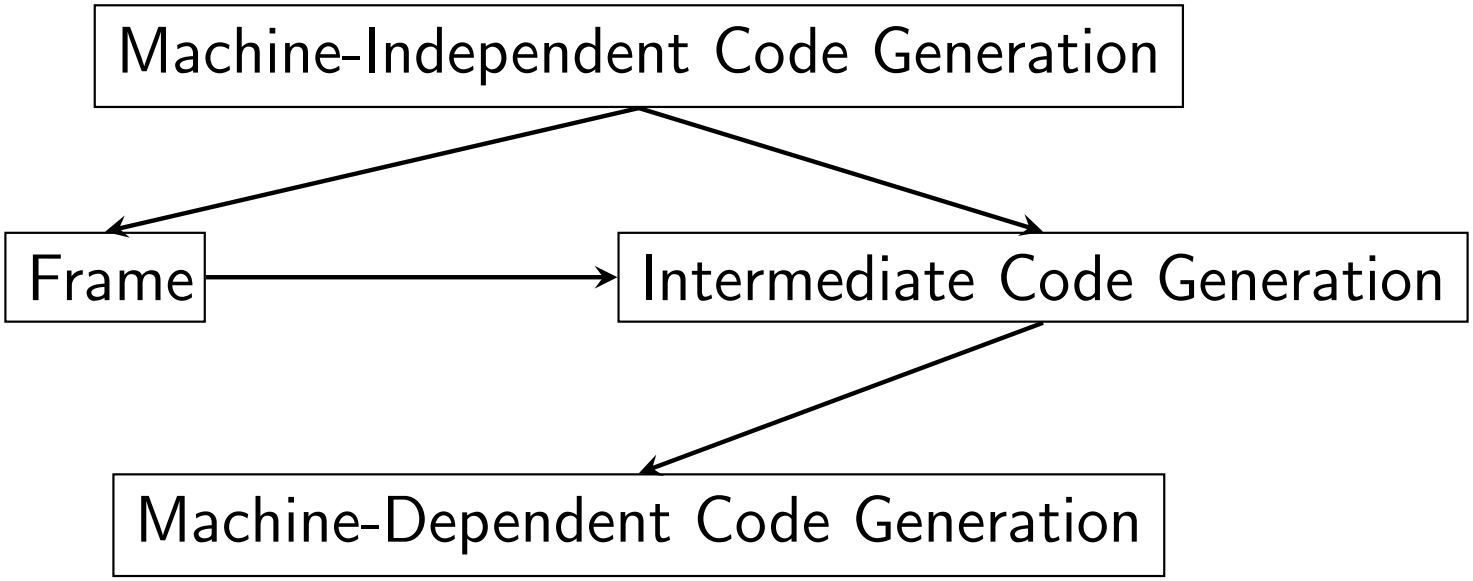
```
while (x.a > 10) do {
    x.a = x.a + 1;
} ;
```

```
aload_2
getfield Main.a I
bipush 10
if_icmple Label0
aload_2
aload_2
getfield Main.a I
iconst_1
iadd
putfield Main.a I
Label0:
```

```
return;
```

```
return
.end method
```

Code Generation Design



Machine-Dependent Code Generation

- Generating specified machine code
  E.g.: emitLDC(20) $\rightarrow$ ldc 20
- Implemented in JasminCode

Intermediate Code Generation

- Depend on both language and machine

Intermediate Code Generation

- Depend on both language and machine
- Select instructions

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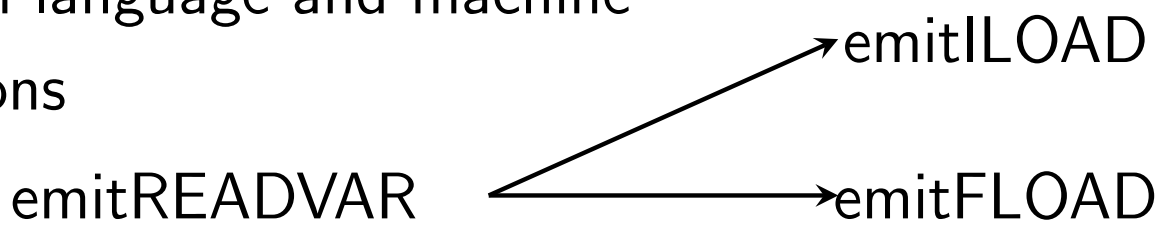
emitREADVAR → emitILOAD

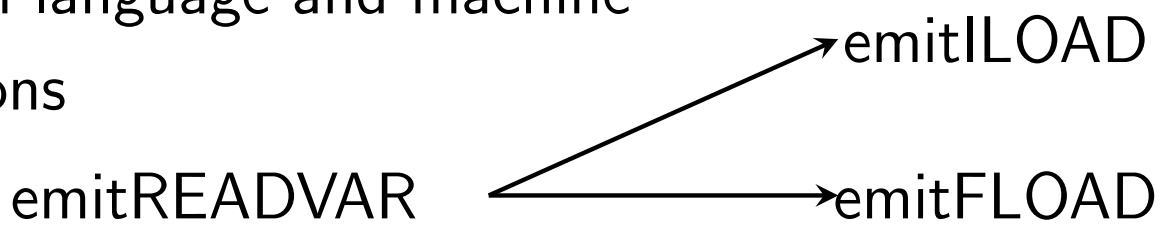
Intermediate Code Generation

- Depend on both language and machine
- Select instructions



Intermediate Code Generation

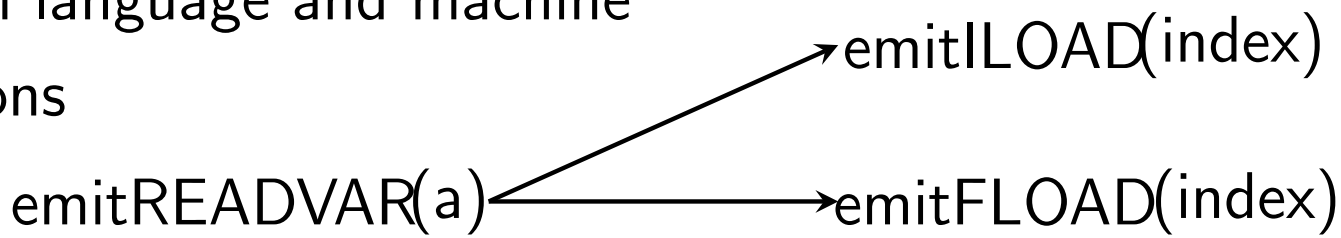
- Depend on both language and machine
- Select instructions



- Select data objects

Intermediate Code Generation

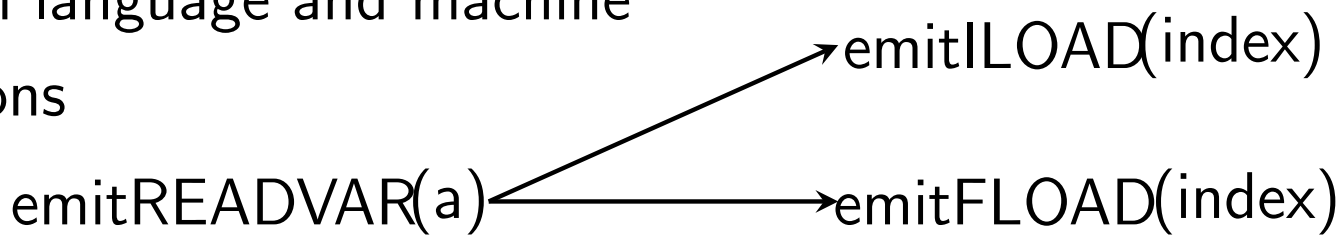
- Depend on both language and machine
- Select instructions



- Select data objects

Intermediate Code Generation

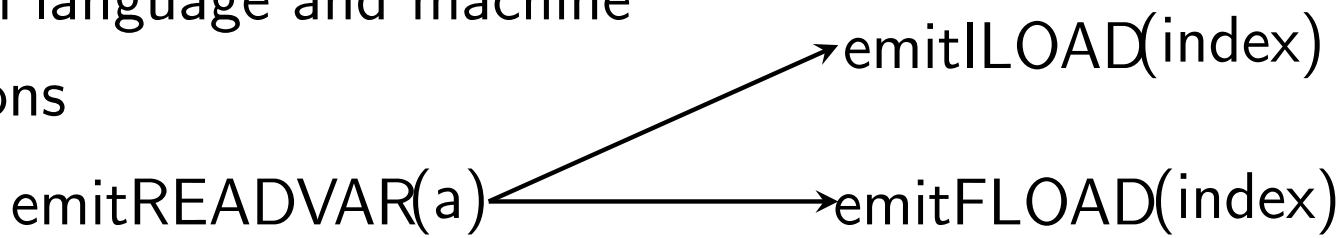
- Depend on both language and machine
- Select instructions



- Select data objects

Intermediate Code Generation

- Depend on both language and machine
- Select instructions



- Select data objects
- Simulate the execution of the machine

Intermediate Code Generation

- Depend on both language and machine
- Select instructions

emitREADVAR(a) → emitILOAD(index)

emitREADVAR(a) → emitFLOAD(index)

- Select data objects
- Simulate the execution of the machine
  - ◁ emitICONST → push()

Intermediate Code Generation

- Depend on both language and machine
- Select instructions

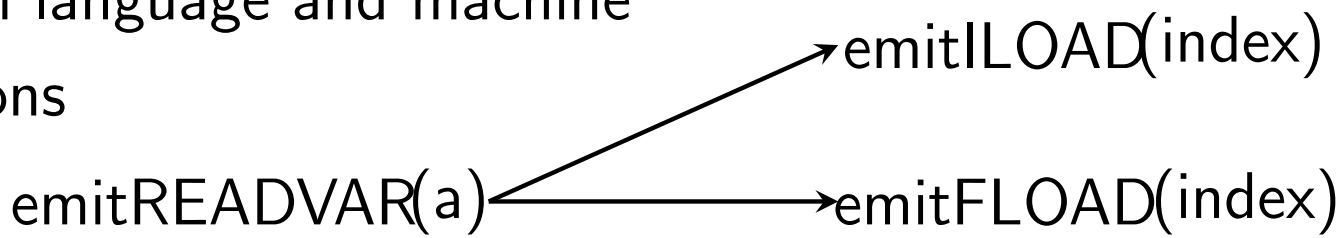
emitREADVAR(a) → emitILOAD(index)

emitREADVAR(a) → emitFLOAD(index)

- Select data objects
- Simulate the execution of the machine
  - ◁ emitICONST → push()
  - ◁ emitISTORE → pop()

Intermediate Code Generation

- Depend on both language and machine
- Select instructions



- Select data objects
- Simulate the execution of the machine
  - ◁ emitICONST → push()
  - ◁ emitISTORE → pop()
- Implemented in class Emitter

Frame

Tools are used to manage information used to generate code for a method

- isMain: generating code for main is different than doing for a normal method
- Labels: are valid in the body of a method
  - getNewLabel(): return a new label
  - getStartLabel(): return the beginning label of a scope
  - getEndLabel(): return the end label of a scope
  - getContinueLabel(): return the label where a continue should come
  - getBreakLabel(): return the label where a break should come
  - enterScope()
  - exitScope()
  - enterLoop()
  - exitLoop()

Frame (cont'd)

- Local variable array
  - getNewIndex(): return a new index for a variable
  - getMaxIndex(): return the size of the local variable array
- Operand stack
  - push(): simulating a push execution
  - pop(): simulating a pop execution
  - getMaxOpStackSize(): return the max size of the operand stack
- Implemented in class Frame

Machine-Independent Code Generation

- Based on the source language
- Use facilities of Frame and Intermediate Code Generation (Emitter)

Outline

Symbol Entries for Local

- String name;
- Type type;
- Kind kind; //Variable, Constant
- Option[String] obj;
  - ◁ the index if id is a local variable
  - ◁ the value of constant

Declarations

- Class Fields
  .field static name type-desc
  - ◁ for an array, generating code to initialize the array in the class init
- Instance Fields
  .field name type-desc
  - ◁ for an array, generating code to initialize the array in the init
  - ◁ for a constant, generating code to initialize the constant in the init
- Local variables
  .var var-index is name type-desc scopeStart-label scopeEnd-label
  - ◁ for an array, generating code to initialize the array in the method
  - ◁ for a constant, generating code to initialize the constant in the method

Method Declarations

- Method Implementation
  .method public class-name/method-name type-desc
  .end method
- How ?

Method Declarations

- Method Implementation
  .method public class-name/method-name type-desc
  .end method
- How ?
  Emitter.emitMETHOD(class-name/method-name, type)
  Emitter.emitENDMETHOD()

Outline

Expressions

- Literals
- Arithmethic expressions
- Boolean expressions
- Relational expressions
- Variables
- Field Access
- Array Cell
- Call

Integer Literals

- Machine code
  - ◁ iconst_m1, iconst_0, iconst_1, ...
  - ◁ iconst <num >
  - ◁ bipush <num >
  - ◁ sipush <num >
  - ◁ ldc <num >
- How ?

Integer Literals

- Machine code
  - ◁ iconst_m1, iconst_0, iconst_1, ...
  - ◁ iconst <num >
  - ◁ bipush <num >
  - ◁ sipush <num >
  - ◁ ldc <num >
- How ?
  emitter.emitICONST(literal,frame)

Arithmetic Expression

```
x.a + 1;
```

```
aload_2
getfield Main.a I
iconst_1
iadd
```

Arithmetic Expression

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x.a + 1;
```

```
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- generate code for operands and then operator
- BinaryOp(op,left,right) $\Rightarrow$

Arithmetic Expression

```
x.a + 1;
```

```
aload_2
getfield Main.a I
iconst_1
iadd
```

- generate code for operands and then operator
- BinaryOp(op,left,right) $\Rightarrow$
  - ◁ visit(ast.left)// generate code for left operand
  - ◁ visit(ast.right) // generate code for right operand
  - ◁ generate code for operators

Relational Expression

$$a > b$$

Relational Expression

$a > b$

```
    iload_2
    iload_3
    if_icmple Label0
    iconst_1
    goto Label1
Label0:
    iconst_0
Label1:
```

Relational Expression

$a > b$

```
    iload_2
    iload_3
    if_icmple Label0
    iconst_1
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Label0:
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Relational Expression

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    goto Label1
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Relational Expression

$a > b$

```
    iload_2
    iload_3
    if_icmple Label0
    iconst_1
    goto Label1
Label0:
    iconst_0
Label1:
```

Relational Expression

$a > b$

```
    iload_2
    iload_3
    if_icmple Label0
    iconst_1
    goto Label1
Label0:
    iconst_0
Label1:
```

Relational Expression

- code for left expr.

$a > b$

```
    iload_2
    iload_3
    if_icmple Label0
    iconst_1
    goto Label1
Label0:
    iconst_0
Label1:
```

Relational Expression

- code for left expr.
- code for right expr.

$a > b$

```
    iload_2
    iload_3
    if_icmple Label0
    iconst_1
    goto Label1
Label0:
    iconst_0
Label1:
```

Relational Expression

$a > b$

```
    iload_2
    iload_3
    if_icmple Label0
    iconst_1
    goto Label1
Label0:
    iconst_0
Label1:
```

- code for left expr.
- code for right expr.
- get 2 new labels

Relational Expression

$a > b$

```
    iload_2
    iload_3
    if_icmple Label0
    iconst_1
    goto Label1
Label0:
    iconst_0
Label1:
```

- code for left expr.
- code for right expr.
- get 2 new labels
- emitRELOP(op,label 1)

Relational Expression

$a > b$

```
    iload_2
    iload_3
    if_icmple Label0
    iconst_1
    goto Label1
Label0:
    iconst_0
Label1:
```

- code for left expr.
- code for right expr.
- get 2 new labels
- emitRELOP(op,label 1)
- code "iconst_1"

Relational Expression

$a > b$

```
    iload_2
    iload_3
    if_icmple Label0
    iconst_1
    goto Label1
Label0:
    iconst_0
Label1:
```

- code for left expr.
- code for right expr.
- get 2 new labels
- emitRELOP(op,label 1)
- code "iconst_1"
- code goto + label 2

Relational Expression

$a > b$

```
    iload_2
    iload_3
    if_icmple Label0
    iconst_1
    goto Label1
Label0:
    iconst_0
Label1:
```

- code for left expr.
- code for right expr.
- get 2 new labels
- emitRELOP(op,label 1)
- code "iconst_1"
- code goto + label 2
- code emitLabel(label 1)

Relational Expression

$a > b$

```
    iload_2
    iload_3
    if_icmple Label0
    iconst_1
    goto Label1
Label0:
    iconst_0
Label1:
```

- code for left expr.
- code for right expr.
- get 2 new labels
- emitRELOP(op,label 1)
- code "iconst_1"
- code goto + label 2
- code emitLabel(label 1)
- code "iconst_0"

Relational Expression

$a > b$

```
    iload_2
    iload_3
    if_icmple Label0
    iconst_1
    goto Label1
Label0:
    iconst_0
Label1:
```

- code for left expr.
- code for right expr.
- get 2 new labels
- emitRELOP(op,label 1)
- code "iconst_1"
- code goto + label 2
- code emitLabel(label 1)
- code "iconst_0"
- code emitLabel(label 2)

Boolean Expressions

- Simple: like arithmetic expression

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- Short-circuit evaluation:

Boolean Expressions

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  - ◁ generate code for the left expression

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  - ◁ generate code to check the result of the left expression

Boolean Expressions

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  - ◁ generate code to check the result of the left expression
  - ◁ generate code for the right expression

Boolean Expressions

- Simple: like arithmetic expression
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Boolean Expressions

- Simple: like arithmetic expression
- Short-circuit evaluation:
  - ◁ generate code for the left expression
  - ◁ generate code to check the result of the left expression
  - ◁ generate code for the right expression

```
(b > 1 && b < 10)
```

```
        iload_2
        iconst_1
        if_icmple Label0
        iload_2
        bipush 10
        if_icmplt Label1
Label0:
```

Outline

Statements

- Block Statements
- Assignment Statements
- If Statements
- While Statements
- Do Statements
- For Statements
- Continue and Break Statements
- Return Statements
- Call Statements

Block Statements

```
{ int a;
  a = 1;
}
{ boolean b;
  b = true;
}
```

```
.var 2 is a I from Label3 to Label4
Label3:
    iconst_1
    istore_2
Label4:
.var 2 is b Z from Label5 to Label6
Label5:
    iconst_1
    istore_2
Label6:
```

Block Statements

```
{ int a;
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```
.var 2 is a I from Label3 to Label4
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```

- frame.enterScope

Block Statements

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{ int a;
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Label4:
.var 2 is b Z from Label5 to Label6
Label5:
    iconst_1
    istore_2
Label6:
```

- frame.enterScope
- generate code for declaration list in the block

Block Statements

```
{ int a;
  a = 1;
}
{ boolean b;
  b = true;
}
```

```
.var 2 is a I from Label3 to Label4
Label3:
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Label4:
.var 2 is b Z from Label5 to Label6
Label5:
    iconst_1
    istore_2
Label6:
```

- frame.enterScope
- generate code for declaration list in the block
- generate the label of the beginning of the block

Block Statements

```
{ int a;
  a = 1;
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```

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.var 2 is a I from Label3 to Label4
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Label6:
```

- frame.enterScope
- generate code for declaration list in the block
- generate the label of the beginning of the block
- generate the code of the block

Block Statements

```
{ int a;
  a = 1;
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  b = true;
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.var 2 is a I from Label3 to Label4
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Label6:
```

- frame.enterScope
- generate code for declaration list in the block
- generate the label of the beginning of the block
- generate the code of the block
- generate the label of the end of the block

Block Statements

```
{ int a;
  a = 1;
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{ boolean b;
  b = true;
}
```

```
.var 2 is a I from Label3 to Label4
Label3:
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    istore_2
Label4:
.var 2 is b Z from Label5 to Label6
Label5:
    iconst_1
    istore_2
Label6:
```

- frame.enterScope
- generate code for declaration list in the block
- generate the label of the beginning of the block
- generate the code of the block
- generate the label of the end of the block
- frame.exitScope

Assignment Statements

Assign(LHS,Expr)

Assignment Statements

Assign(LHS,Expr)

- Id
- Field Access
- Array Cell

If Statements

```
if (a > b)
    c = 1;
else
    c = 2;
```

```
    iload_1
    iload_2
    if_icmple Label1
    iconst_1
    goto Label2
Label1:
    iconst_0
Label2:
    ifeq Label3
    iconst_1
    istore_3
    goto Label4
Label3:
    iconst_2
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Label4:
```

If Statements

```
if (a > b)
    c = 1;
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        iload_1
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    Label2:
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- code for expr

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- code for expr
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- get 2 new labels
- code "label1"

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```

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- code "label1"
- code for expr
- code "ifeq" + label2
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- code "goto" + label1
- code "label2"

Break and Continue Statements

When generating code for a body of a loop, how to generate code for a **break** or **continue** statement?

Break and Continue Statements

When generating code for a body of a loop, how to generate code for a **break** or **continue** statement?

- Frame.enterLoop
  - create 2 new labels **continueLabel** and
  - breakLabel
  - put these labels onto **continueStack** and **breakStack**
  - **Frame.getContinueLabel** and **Frame.getBreakLabel** return these labels

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  - ◁ put these labels onto **continueStack** and **breakStack**
  - ◁ **Frame.getContinueLabel** and **Frame.getBreakLabel** return these labels
- Frame.exitLoop
  - ◁ pop these labels out of **continueStack** and **breakStack**
- continue; ⇒ emitter.emitGOTO(frame.getContinueLabel)
- break; ⇒ emitter.emitGOTO(frame.getBreakLabel)

Revised While Statements

```
while (a > b) do
    a = a - 1;
```

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Label1:
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- frame.enterLoop
- get breakLabel and continueLabel

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Do and For Statements

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Do it yourself

Call Statements

Call Statements

Look in the initial code

Outline

Jasmin Directives

Jasmin Directives

Look in the initial code

Summary

- Use BCEL to know which code should be generated

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Summary

- Use BCEL to know which code should be generated
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- Good luck